A PREDICTIVE MODEL OF MASS LOSS IN SENSITIZED 5XXX ALUMINUM ALLOYS

by

Alexander Derrick

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Metallurgical Engineering

The University of Utah

May 2016

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of **Alexander Derrick**

has been approved by the following supervisory committee members:

Michael L. Free	, Chair	**May 13, 2015** Date Approved
Sivaraman Guruswamy	, Member	**May 13, 2015** Date Approved
Zhigang Zak Fang	, Member	**May 13, 2015** Date Approved

and by **Manoranjan Misra** , Chair/Dean of

the Department/College/School of **Metallurgical Engineering**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Aluminum magnesium alloys, due to their high strength and overall corrosion resistance, are used more and more in a variety of applications, from automobiles to navy ships. The addition of magnesium greatly increases the strength of aluminum. However, at elevated temperatures beta phase particles (Al_2Mg_3) can precipitate along grain boundaries and lead to intergranualar corrosion and stress corrosion cracking. The corrosion of these alloys has been widely studied and the ASTM G67 standard mass loss test is used to compare the degree to which the alloy has been sensitized by the formation of beta phase particles. A simple model was developed, based on the ASTM G67 test, in order to predict the mass loss of an aluminum alloy, given several key parameters, such as beta phase thickness and continuity of the beta phase along the grain boundary. The model was validated through SEM, TEM, and AFM imaging. This mass loss model was combined with previous work, which estimates key parameters, creating a predictive tool to allow for useful projections of service life in 5xxx aluminum alloys.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Background

Aluminum alloys are of particular interest, due to their resistance to many forms of corrosion, as well as their strength to weight ratio. This is even more pronounced in applications where reducing weight allows a corresponding increase in capacity, such as in marine applications. In particular, Aluminum 5000 series alloys demonstrate superior mechanical properties, due to the addition of magnesium, while retaining the corrosion resistance of the base metal. However, despite these advantages, these alloys are known to experience intergranualar corrosion and stress corrosion cracking, which can lead to premature mechanical failure.

Research has shown that the susceptibility of 5000 series Aluminum alloys to intergranular corrosion and stress corrosion cracking is primarily caused by the precipitation of β phase (Al_3Mg_2) particles along the grain boundary of the aluminum microstructure. The precipitation occurs at moderate temperatures, due to the diffusion of magnesium from the bulk into the grain boundaries. As this diffusion takes place, regions of concentrated magnesium are formed in the grain boundary, leading to β phase formation. β phase formation makes the metal more sensitive to corrosion. Correspondingly, the formation of beta phase is also the process of sensitization in 5xxx aluminum alloys.

The level of sensitization is quantified using the standard ASTM G67 mass loss test, where the sample is immersed in concentrated nitric acid for 24 hours at 30 °C, and the mass loss is measured. Much research has been done to understand the β phase precipitation and the factors that affect how and to what extent this sensitization occurs at a given set of conditions. With this information, however, a correlation to the mass loss of the sample is needed to predict the sensitization of a material, knowing the service conditions in which the material is used.

The Nitric Acid used in the test preferentially dissolves the precipitated β phase particles along the grain boundary. This leads to the removal or fallout of the grains, once the acid has penetrated to the next grain. Given the low rate of pure aluminum dissolution in concentrated nitric acid, the measured mass loss of the sample is often dominated by the mass removed due to grain fallout. As such, the mass loss of the sample can be correlated from the grain fallout to the penetration depth of the nitric acid.

1.2 Objective

A mathematical model that predicts the degree of sensitization, as measured by the ASTM G-67 test, has been developed. Specifically, the model has been developed in two sections. The first predicts β phase continuity as a function of exposure time and temperature as well as various alloy parameters, such as type, heat treatment, etc. The second predicts the degree of sensitization as a function of the β phase continuity of the material. Thus, the combination of both models gives the degree of sensitization as a function of the material and service conditions. The model is based on longer exposure times at lower temperatures, focusing on replicating actual material service conditions. Specifically, exposure times up to 30 months and temperatures ranging from 40-70 °C have been evaluated and used in the model development. The focus of this work is on the development and validation of the second portion of the model, predicating mass loss results, based on β phase continuity of a sample.

2 LITERATURE REVIEW

2.1 Aluminum 5000 Series Alloys

2.1.1 Introduction

With the expanded use of aluminum alloys, especially in naval applications, following the end of World War II, research into these alloys has been ongoing through the later half of the 20th century. [3] In particular, focus on the aluminum-magnesium alloy, otherwise known as the 5000 series, has been of specific interest due to its comparable strength to low alloy steels with a weight reduction between 50-60%. [9] These alloys demonstrate good machinability with a greatly increased corrosion resistance, more than 100 times slower compared to low alloy steel. [9] Given these benefits, aluminum 5000 series alloys have been in wide use in naval applications for the past half-century and have been the center of much research. Despite these advantages, these alloys are known to be susceptible to both intergranualar corrosion (IGC) and stress corrosion cracking (SCC) due to the precipitation of an intermetallic β phase (Al_3Mg_2) along the grain boundary. In light of this limitation, a predictive tool would be a great benefit in determining the level of corrosion susceptibility of an alloy and predicting the life before failure of the material. Such a tool would also allow for appropriate preventative maintenance and part replacement to occur when needed, while limiting the associated costs of testing and down time of the equipment. This research focuses on developing such a tool specifically for naval applications.

2.1.2 Alloy Series And Temper Designations

Given the wide variety of aluminum alloys in use, it is important to first understand what types of alloys are being investigated before a predictive model can be developed. To assist in understanding, a standardized set of naming conventions has been developed in order to catalog the various aluminum alloys into several categories. This designation system, developed by the Aluminum Association, imparts meaningful information on the chemical composition and characteristics of an alloy. The system is composed of a four-digit number and is sometimes accompanied by alphanumeric prefixes or suffixes. The meaning of these fours numbers is described in Table 1. [5]

Specifically, the 5000 series represents aluminum alloys with magnesium as the major alloying element. In conjunction with these standard four digits, a temper designation system is also utilized to specify the temper of the alloy as well. This designation begins with one of five capital letters, as defined in Table 2. [5]

The subdivisions involve the addition of one of more digits following the first letter. The first digit indicates which specific basic operations were used on the alloy, as described in Table 3. [5]

Table 1 – Overall aluminum alloy naming convention

Digit Place	**Description**
First Digit	"...defines the major alloying class of the series starting with that number." [5]
Second Digit	"... defines variations in the original basic alloy: that digit is always a zero (0) for the original composition, one (1) for the first variation, two (2) for the second variation, and so forth. Variations are typically defined by differences in one or more alloying elements of 0.15 to 0.50% or more, depending on the level of the added element." [5]
Third & Fourth Digit	"...designate the specific alloy within the series; there is no special significance to the values of those digits, nor are they necessarily used in sequence." [5]

Within the temper designation system, there are subdivisions for each temper designation. As only H tempers have been investigated in this research, only these subdivisions will be explained. The subdivisions involve the addition of one or more digits following the first letter. The first digit indicates which specific basic operations were used on the alloy, as described in Table 3. [5]

Typically, the next digit, which follows these designations, represents the relative hardness of the alloy. For this digit, the hardest or most strain hardened value assigned to an alloy is 8 (i.e., HX8). Furthermore, the value representing half the strain hardening of a value of 8 would be a value of 4, or in other words, an alloy that is strain hardened to half of the ultimate hardness would be an HX4 temper. This pattern continues with half of a 4 being a 2 and so forth for all the values. Finally, some temper designations include a third digit. There are a variety of standardized three-digit temper designations, each with a specific meaning. [5]

Table 2 – Main temper designations

Main Temper Designation	**Description**
F (as fabricated)	"Applies to wrought or cast products made by shaping processes in which there is no special control over thermal conditions or strain-hardening processes employed to achieve specific properties. For wrought alloys there are no mechanical property limits associated with this temper, although for cast alloys there generally are." [5]
O (annealed)	"Applies to wrought products that are annealed to obtain the lower strength temper, usually to increase subsequent workability. The O applies to cast products that are annealed to improve ductility and dimensional stability and may be followed by a digit other than zero." [5]
H (strain hardened)	"Applies to products that have their strength increased by strain hardening. They may or may not have supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits" [5]
W (solution heat-treated)	"Applies only to alloys that age spontaneously after solution heat-treating. This designation is specific only when digits are used in combination with W to indicate the period of natural aging, for example, W 1/2 hr." [5]
T (thermally treated to produce stable tempers other than F, O, or H)	"Applies to products that are thermally treated, with or without supplementary strain hardening, to produce stable tempers. The T is always followed by one or more digits." [5]

Table 3 – H temper subdivision designations

Main Temper Designation	**Description**
H1 (strain hardened only)	"Applies to products that have been strain hardened to obtain a desired level of strength without a supplementary thermal treatment. The number following H1 indicates degree of strain hardening." [5]
H2 (strain hardened and partially annealed)	"Applies to products that have been strain hardened more than the desired final amount, and their strength is reduced to the desired level by partial annealing. The number added to H2 indicates the degree of strain hardening remaining after partial annealing." [5]
H3 (strain hardened and stabilized)	"Applies to products that have been strain hardened and then stabilized either by a low temperature thermal treatment, or as a result of heat introduced during fabrication of the product. Stabilization usually improves ductility. The H3 temper is used only for those alloys that will gradually age soften at room temperature if they are not stabilized. The number added to H3 indicates the degree of strain hardening remaining after stabilization" [5]
H4 (strain hardened and lacquered or painted)	"Applies only to alloys that age spontaneously after solution heat-treating. This designation is specific only when digits are used in combination with W to indicate the period of natural aging, for example, W 1/2 hr." [5]
T (thermally treated to produce stable tempers other than F, O, or H)	"Applies to products that are strain hardened and that have been subjected to heat during subsequent painting or lacquering operations. The number added to H4 indicates the amount of strain hardening left after painting or lacquering." [5]

However, not all three-digit combinations have been standardized, and thus care must be exercised in determining information on the alloy temper from these designations. [5]

Based on an understanding of these two designation systems, much can be understood about a specific alloy immediately. For instance, a 5083-H116 alloy is an aluminum alloy of the first series, where magnesium is the main alloying element. In addition, this alloy is only strain hardened to one eighth ($^1/_8$) of the ultimate hardness of the alloy.

2.2 β Phase Precipitation

Because the corrosion of 5000 series aluminum alloys occurs due to the precipitation of intermetallic β phase particles, to accurately predict the level of precipitation of β phase (commonly referred to as sensitization) in 5000 series aluminum alloys, it is essential to understand the precipitation process. This includes the causes of precipitation, how and where the precipitation takes place as well as what material properties affect this process. This precipitation is not only limited to β phase particles as other intermetallics can also precipitate in 5000 series alloys. Figure 1 and Figure 2 show scanning electron microscope and transmission electron microscope images of the aluminum microstructure.

In Figure 1, the β phase particles can be seen as the black spots, whereas the other intermetallics are apparent as lighter particles of significantly larger size.

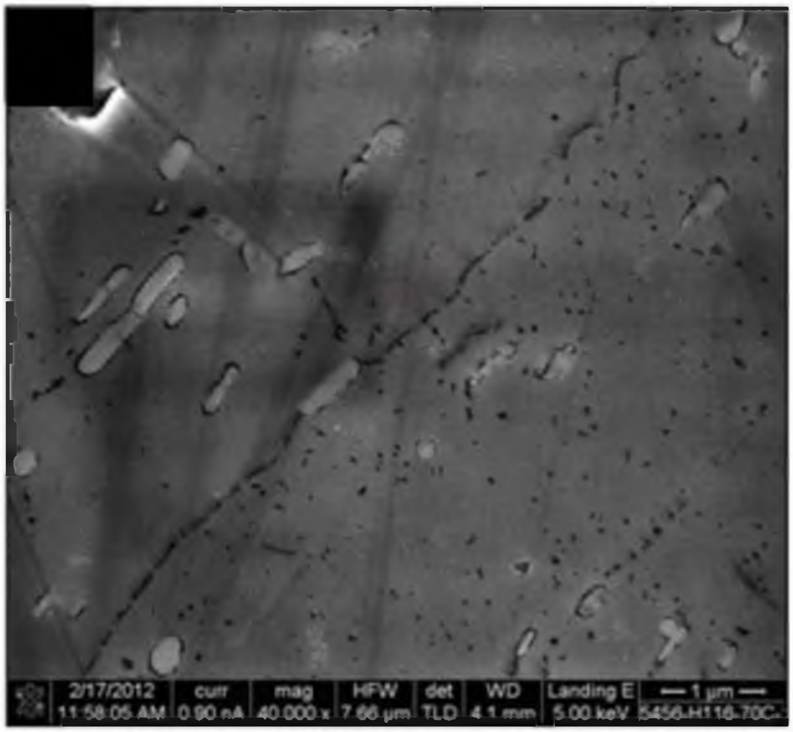

Figure 1 – SEM micrograph of aluminum microstructure [60]

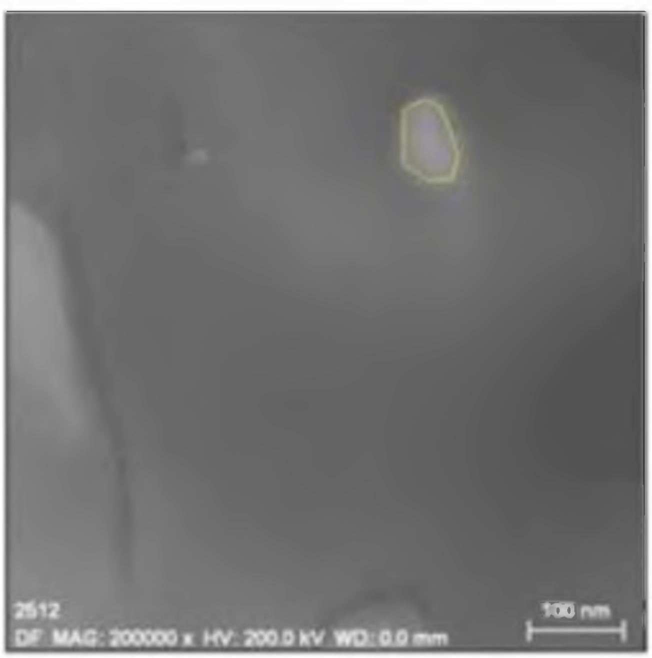

Figure 2 – TEM micrograph of aluminum microstructure [60]

In Figure 2, the β phase particles can be seen as the black line along the left hand side, whereas the other intermetallics are apparent as lighter particles of significantly larger size, same as in the scanning electron microscope image. Of the variety of intermetallic precipitates that can and do exist within the aluminum alloy, it is the β phase particles that increase the corrosion susceptibility of aluminum.

2.2.1 Aluminum Magnesium Phase Diagram

A logical starting point for understanding this process begins with the phase diagram for the aluminum magnesium system, shown in Figure 3. Based on this diagram, the temperature at which magnesium concentrations around 5% are soluble within the aluminum matrix is around 250 °C. Below this temperature, there exists a thermodynamic equilibrium between magnesium soluble within the aluminum base metal and precipitated β phase, at the specific temperature of interest. As such, there is a thermodynamic driving force for β phase precipitation at typical temperatures for naval applications (less than 70 °C).

2.2.2 Precipitation Series

With this basic understanding of why precipitation occurs, much research has been done to study how the β phase precipitates. Nozato and Ishihara [16] studied the precipitation of β phase particles through calorimetric means.

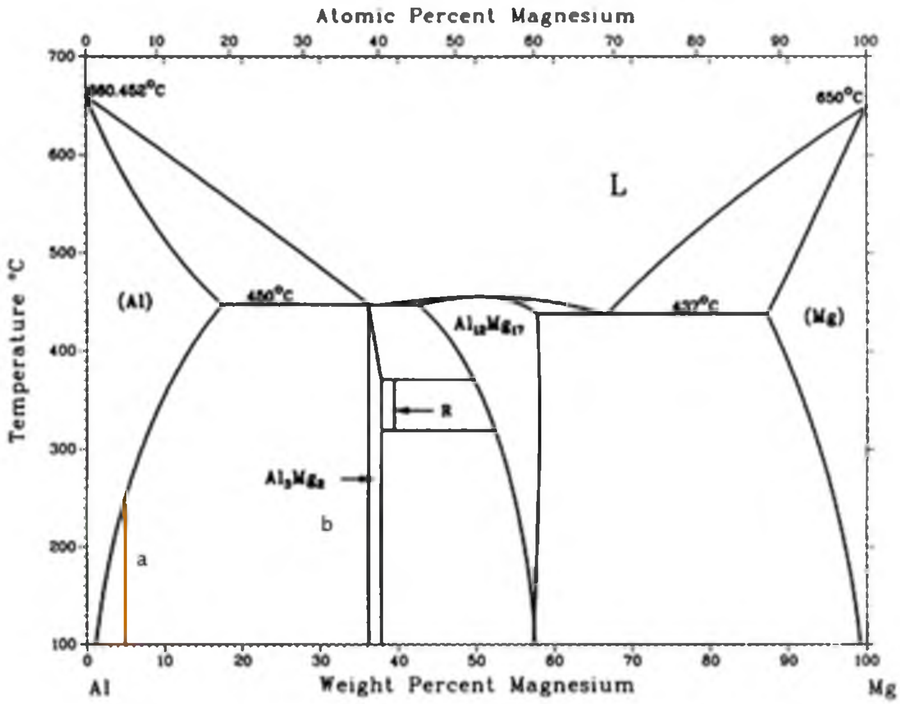

Figure 3 – Aluminum-magnesium phase diagram. The magnesium concentration of interest (around 5%) is shown (a) and the β phase can be seen (b). [17]

According to their findings, the process can be described through four steps, beginning with the formation of Guinier–Preston (GP) zones. GP zones are small regions enriched with magnesium that form the first step of β phase precipitation. Following their formation, metastable β'' and β' phase are formed as intermediates, until the equilibrium β phase forms, as shown in Equation 1.

$$Al\ matrix \rightarrow GP\ zones \rightarrow \beta''phase \rightarrow \beta'\ phase \rightarrow \beta\ phase$$

Equation 1

In addition, they showed that the precursor β phases (GP zones and β'') precipitate at lower temperatures, specifically less than 90 °C and that as the temperature increased the stable phase would follow the precipitation sequence. [16] Their findings correlated well with those of Nebti *et al*. [12], who showed that precursor β phases (GP zones and β ”) are stable until 100 °C, the β ’ phase is stable until 250 °C and above this temperature, the β phase is the stable phase. Given the difficulty in detecting GP zones, several researchers, including Bernole *et al.* [18], Boudili *et al.* [19], and Gault *et al.* [20], have investigated these alloys aged at room temperature using transmission electron microscope (TEM) and X-ray techniques, showing the existence of these zones in various alloys. In addition, TEM and X-ray techniques were used by Kubota [14] to show the presence of β phase in samples aged at higher temperatures, around 240 °C. Starink *et al.* [15] also investigated precursor β phases using differential scanning calorimetry showing the β ’ precipitation can occur independently of both GP zone and β ” formation. Furthermore, alloys sensitized at higher temperatures, around 175 °C, showed almost complete β phase with little to no precursor β phases present. [2] In addition to these general trends, Searle *et al*. [23] and Yi *et al*. [24] showed that at longer aging times, β and β ’ precipitates can also occur at lower temperatures, around 70 °C. Based on these findings, it is reasonable that at temperatures around 70 °C, both precursors and full β phase precipitates can occur within the material, leading to corrosion problems.

2.2.3 Precipitation Effects

In addition to understanding how β phase precipitation occurs, it is also important to understand what material properties can affect precipitation as well as understanding where precipitation occurs. It is apparent from the phase diagram that the magnesium concentration of the specific alloy in question affects the driving force for β phase precipitation i.e., the higher the concentration of magnesium within the aluminum matrix, the higher the driving force. Niederberger *et al.* [3] showed this effect as they studied stress corrosion cracking in a seawater environment. According to their results, failures due to corrosion were observed exclusively in the higher magnesium concentration alloys tested. The effects of magnesium concentration were also observed by Nozato and Shinobu [16], as higher concentration alloys, around 12.5%, were prone to concurrent precipitation of β phase, along with β'' and β'. Nebti *et al.* [12] also saw evidence of this effect as higher concentration alloys, around 12% Mg, rapidly form GP zones after quenching, whereas lower concentrations, around 8%, undergo the transformation process at room temperature of many years.

Precipitation of these phases occurs almost exclusively along grain boundaries or preexisting particles. Goswami *et al.* [1],[2] verified this fact through TEM of a sample sensitized at 175 °C as well as through simple thermodynamic calculations, showing that the driving force for β phase nucleation is small, thus making grain boundaries and preexisting particles the ideal location for precipitation. In addition, Zhu *et al.* [25] found that dislocations within the aluminum matrix also contribute to the precipitation of β phase. Unwin *et al.* [36] studied the effect of the grain boundary structure on the β phase precipitation and found that precipitation and growth were strongly affected by the type of grain boundary. As a result, several authors including Kaigorodava [35], Saito *et al.* [37], and Tan [38] have investigated the control of grain boundary characteristics through further processing.

Both of these effects are critical to the corrosion of aluminum alloys and therefore must be understood to properly predict the corrosion of these alloys.

2.3 β Phase Corrosion

With this basic foundation in understanding β phase precipitation, comprehending the causes and effects of the corrosion of the aluminum alloy is also of great importance to develop a model. As with the β phase precipitation, much research has been performed to determine how β phase affects the corrosion of the aluminum as well as to investigate other material properties that play a role in corrosion. Much of the research in this area is based in part on the work of previous researchers, such as Gehring *et al.* [32] and Nguyen *et al.* [33] who did early studies on various aluminum alloys, specifically looking at corrosion in general.

Building on these earlier studies, Barbucci *et al.* [30] investigated how the presence of the alloying elements, such as magnesium, affect the passive aluminum oxide film and found that the corresponding precipitates weaken this protective film and lead to pitting and further corrosion. Niederberger *et al.* [3] conducted long-term corrosion tests on aluminum 5000 series in sea water and investigated the effects of alloy type, temper, sensitization time and exposure time to the corrosive environment. Their results indicated that corrosion of the alloy was dependent on the sensitization time or time under which the alloy was exposed to elevated temperatures rather than exposure time to the corrosive environment. Consequently, exposure times up to 10 years showed little to no corrosion on as milled samples, whereas samples sensitized at 175 °C for one week displayed signs of corrosion less than one year into the corrosion testing. In addition, the samples with more magnesium exhibited greater susceptibility to corrosion.

As mentioned previously, intergranualar corrosion (ICG) and stress corrosion cracking (SCC) are associated with the effects of sensitization and the corrosion susceptibility of aluminum alloys. ICG is corrosion along the grain boundaries within a material whereas SCC is corrosion enhancement due to applied stresses in a corrosive environment. Figure 4 shows an example of both corrosions.

Pickens *et al.* [26] showed that hydrogen played a role in these two forms of corrosion within aluminum, implying that the corrosion may not be tied to β phase precipitation. However, Searle *et al.* [23] found that without β phase precipitation, SCC does not occur in 5000 series alloys. In addition, they used constant-extension-rate testing in order to evaluate both of these phenomena as well as to investigate the relationships between β phase precipitation and SCC and ICG. Their results showed that β phase precipitation is necessary for SCC in the aluminum alloy. In addition, Jones *et al.* [8] found an increase in the crack growth rate in 5083 of

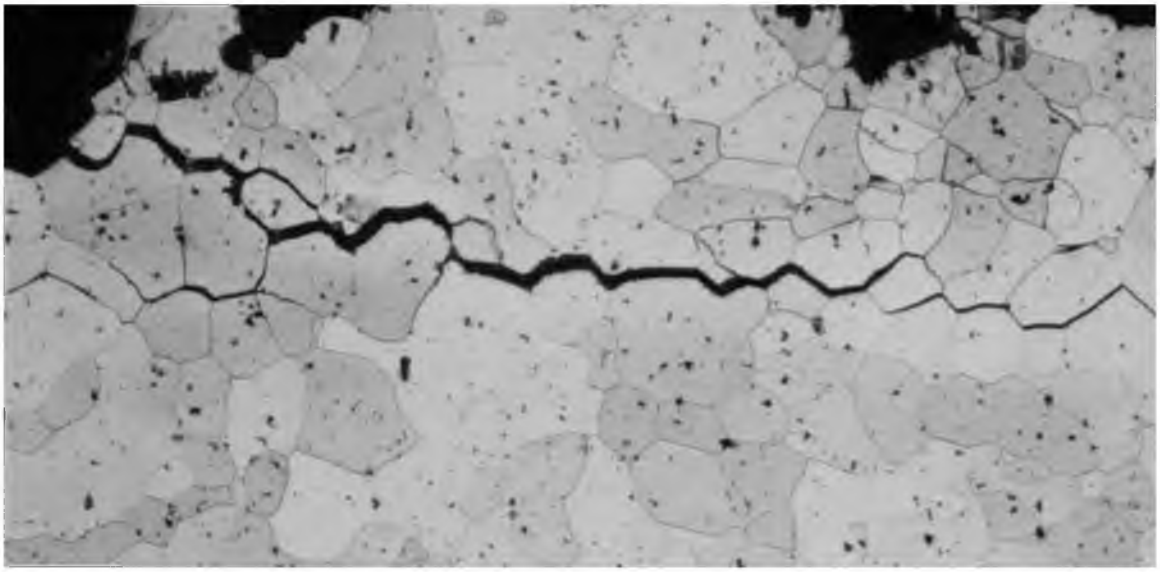

Figure 4 – SEM showing both intergranualar corrosion and stress corrosion cracking in an aluminum alloy [29]

around five times due to the presence of β phase precipitates. Holtz *et al.* [31] further defined this correlation by reviewing its effect with regards to the load ratio and the degree of sensitization.

Their results confirmed that there is a sensitization threshold under which the presence of β does not significantly affect the corrosion. They also found that at high load ratios the effect of β phase on corrosion fatigue is increased. Lim *et al.* [42] found that in addition to degree of sensitization or the amount of β phase present, the temperature under which β phase precipitation is allowed to occur also influences the corrosion characteristics of the material. All of these results have led to the wide acceptance that β phase precipitation is the main cause of SCC and ICG in aluminum 5000 series alloys. As a result, current work is being done to develop models to predict both ICG and SCC in aluminum 5000 series alloys [39]-[41].

The effect of alternative intermetallic particles on corrosion in other alloys has also been investigated, specifically in aluminum 2000 and 6000 series. As with β phase precipitates, other intermetallic precipitates also contributed to the corrosion of their respective alloys [44] - [51]. In addition to the effect of these precipitates on the corrosion of aluminum alloys, other material characteristics should also be considered. Yuan [34] investigated the grain boundary characteristics, specifically the misorientation angle between grains and found that the depth of intergranualar attack showed a correlation with this property, specifically an increasing depth with increased misorientation.

2.3.1 Electrochemical Aspects

The effect of β phase on the corrosion of aluminum is tied to the electrochemical nature of the system. The β phase precipitates along the grain boundaries dissolve as a result of the difference in the electrochemical characteristics between the β phase and aluminum matrix when exposed to a corrosive environment. There exists a large difference in open circuit potential (OCP) between the aluminum matrix and the precipitated β phase particles, leading the precipitates to be anodically active compared to the base aluminum material. This difference in OCP leads to the dissolution or corrosion of the β particles due to the galvanic coupling of the two dissimilar materials. [8], [11] In this coupling, the

β phase acts as the anode to the aluminum matrix cathode, creating an electrochemical cell and leading to β phase corrosion and degradation of the typical oxide film inherent on the aluminum matrix under typical conditions. [7], [8]

Birbilis *et al.* [27] studied a variety of intermetallic particles within several aluminum alloy systems, determining the corrosion potential of these particles in various salt solutions. Their data show a clear potential difference between the β phase particles and the aluminum alloy, with the β phase having a lower corrosion potential than that of the matrix. The values for the β phase and base aluminum within a typical salt solution are listed in Table 4.

Windisch *et al.* [11] explored the changes in OCP in seawater due to the addition of magnesium and found accelerated corrosion in both high and low pH environments, verifying the negative effects of β phase precipitation. Searles *et al.* [23] also investigated the electrochemical aspects of β phase assisted corrosion and found a distinct correlation between the presence of β phase and the overall corrosion of the aluminum. Specifically, they found that samples polarized below

Table 4 – Corrosion potentials of Aauminum and β phase precipitates [27]

Formula	Phase	Corrosion Potential (mV_{SCE})
Al	-	-823
Al_3Mg_2	β	-1013

the β phase breakdown potential showed little to no signs of SCC and ICG, giving clear indication that β dissolution is the main contributing factor to the corrosion of sensitized 5xxx aluminum. Schmutz [43] confirmed this result with studies by scanning kelvin probe force microscopy, finding significant differences in Volta potential between the aluminum matrix and a variety of intermetallic particles.

2.3.2 Physical Aspects

Based on the electrochemical nature of β phase dissolution, the physical corrosion and degradation of the aluminum alloy is due to grain fallout, as the β phase precipitates along the grain boundary are dissolved, leading to lack of cohesion between this grain and the bulk of the aluminum alloy. This correlates well with the results of Sharma *et al.* [22] and Kus *et al.* [21] showing the presence of large pits in conventional aluminum 5083 alloys after sensitization. Pitting is known of to be particular importance in aluminum alloys, especially with intermetallic precipitates such as β phase. Given the potential difference between these particles and the aluminum matrix, these precipitates will preferentially dissolve, leaving pits in the material. [28] When the sensitization of the sample increases, however, the pit left by the dissolution of these precipitates will lead to grain fallout. Thus, as sensitization increases, the effect of grain fallout becomes more critical to the overall corrosion of the aluminum.

2.4 ASTM G67 Mass Loss Test

The standard ASTM G67 mass loss test was developed to quantify the level of sensitization within an aluminum 5000 series alloy. According to the standard, a specific orientation of an aluminum alloy is cut to a specified size, polished to a define roughness, and submersed in concentrated nitric acid at 30 °C for 24 hours. During this time, the nitric acid will dissolve the β phase precipitates, leading to mass loss from the sample. Following the test, the differential mass lost per area is calculated to determine the level of degradation the sample has undergone. Based on the results of this test, several categories have been established to define the level of sensitization. A mass loss measurement from 0 to 15 mg/cm^2 is defined as no sensitization, between 15 and 25 mg/cm^2 is identified as intermediate sensitization and above 25 mg/cm^2 is categorized as full sensitization. [4]

2.5 Conclusion

The precipitation of β phase in aluminum 5000 series alloys has been the area of extensive research during the previous decade. This research has focused on understanding how and why β phase precipitation occurs and its effects on the overall corrosion, both intergranualar and stress corrosion cracking, of an aluminum alloy. In addition, there have been several models developed to predict SCC and ICG for these alloys. However, little to no research has been done to bridge the gap between β phase precipitation and corrosion and the quantifiable results given by the G67 mass loss test. Thus, given the current research of β phase precipitation and corrosion, modeling and predictive analysis on aluminum alloys are limited to prediction of corrosion rates and β phase growth, without any comparison to level of sensitization as defined by the G67 test. For a model to be of most use, however, these two points must be connected with further research to understand the connection between β phase corrosion and the test results. With this bridge, the current understanding of β phase precipitation and corrosion can be applied and readily used for sensitization prediction in real world applications. In the current research, the focus has been placed on understanding the ASTM G67 mass loss test and the correlation between the test results and the β phase precipitation within an aluminum sample, to accurately predict the sensitization of the alloy.

3 EXPERIMENTAL METHODS

3.1 Materials

Commercial aluminum magnesium alloys 5083 and 5456 of varying tempers were used in this work. Alloys 5083-H131 and 5083-H116 alloys were supplied by Alcoa and alloys 5083-H321 and 5456-H116 alloys were purchased from Pierce Aluminum.

3.2 Sample Preparation

3.2.1 Scanning Electron Microscopy

Samples for scanning electron microscopy (SEM) were cut with rough dimensions of 8 x 8 x 8 mm. These were mounted in an epoxy mixture (epoxy resin with epoxy hardener in the ratio of 10:4) and cured for a minimum of 24 hours. The samples were then polished with a series of silicon carbide polishing papers, 240 grit to 4000 grit, followed by 3 and 1 micron diamond pastes and finally with a 0.05 micron colloidal alumina suspension. The samples were etched at room temperature for 1 minute in concentrated (70%) nitric acid.

3.2.2 Atomic Force Microscopy

Samples for atomic force microscopy (AFM) were taken from those used previously in the SEM and followed a similar procedure. These samples were not mounted in epoxy. However they did follow the same polishing steps of silicon carbide paper, followed by diamond pastes and an aluminum suspension. Once polished, the samples were ion milled using a Fischione 1060 SEM mill for 1.5 hours as a final preparation step.

3.2.3 Nitric Acid Mass Loss Testing

Samples for nitric acid mass loss testing (NAMLT) were sectioned from the bulk aluminum plate with rough dimensions of 50 x 25 x 5 mm, according to Figure 5.

Each sample was polished to a smooth finish using 240 grit silicon carbide polishing paper and each dimension was measured at both ends of the sample with calipers. The sample was immersed in 5% NaOH solution at 80 C for 1 minute, followed by a water rinse. The sample was again immersed in a concentrated (70%) nitric acid at 30 C at room temperature for 30 seconds, followed by a water rinse and air dry. The sample weight was taken on a Fisher Scientific Accu 225D scale, measured to four decimal place accuracy. The acid testing was completed according to the standards defined in ASTM G67. The samples were rinsed again in water and brushed with a wire brush, to ensure removal of all disconnected pieces. The final weight was taken and the mass lost per unit area was calculated.

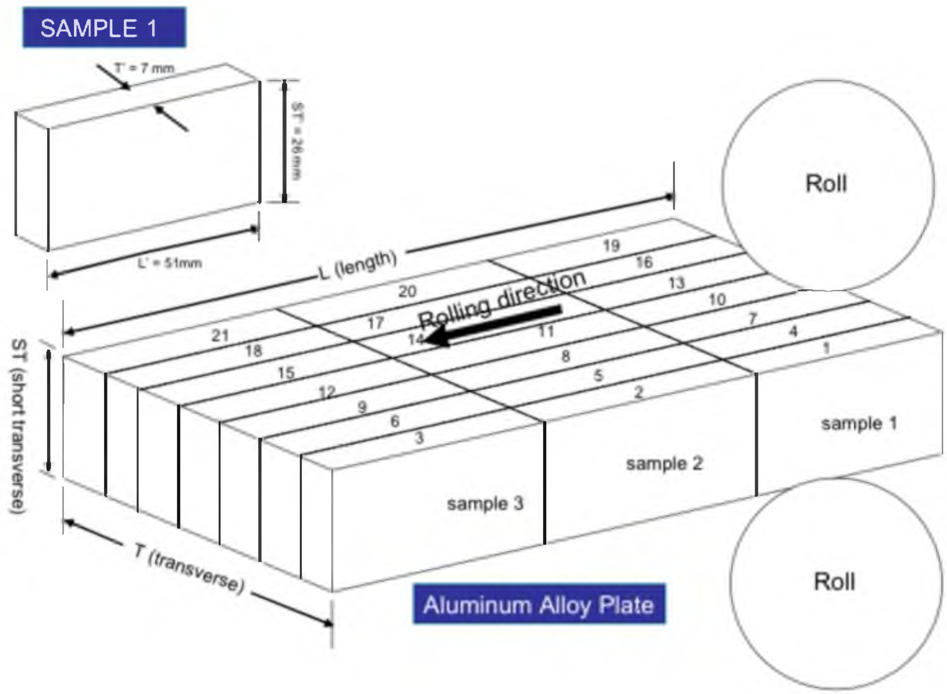

Figure 5 – Schematic of sample sections from the bulk [57]

In addition to the standard ASTM G67 test, two variations were also conducted to quantify the dissolution of aluminum and β phase in nitric acid. The same setup was used for both. For one set of experiments, the nitric acid concentration was varied, using concentrations of 46.7%, 23.3% and 7% nitric acid at the standard test temperature of 30 °C. For the second set, the standard acid concentration of 70% was used at a elevated temperature of 50 °C. This allowed for a better understanding of the affect of temperature and acid concentration on the mass loss of sensitized 5xxx aluminum.

3.3 Sample Characterization

3.3.1 Scanning Electron Microscopy

A FEI Nova NanoSEM SEM was used to image the grain boundaries of the samples for the presence β phase precipitates. 8kV acceleration potential was used and the secondary electrons collected for imaging. Between 20 and 70 different grain boundaries were imaged for each sample.

3.3.2 Atomic Force Microscopy

A JPK Nanowizard 3a Ultra AFM was used to image the grain boundaries of the samples for the presence β phase precipitates as well as examine the dissolution rate of the beta phase, aluminum matrix along the grain boundary and detect any additional dissolution characteristics when exposed to nitric acid and phosphoric acid. Contact mode was used for all imaging.

The samples were initially mounted on the AFM stage using carbon tape. An initial etch was utilized (15 seconds for nitric acid and 30 seconds for phosphoric acid) in order to view the β phase particles in the AFM. Once engaged, images were taken of several β phase particles as well as different grain boundary areas within the AFM image range. The AFM head was then removed and the sample was etched repeatedly over various additional etching times to view the progression of β phase and grain boundary dissolution.

3.3.3 β Phase Measurements

To measure the β phase thickness and continuity within the samples, the SEM micrographs were overlayed with equally spaced lines, perpendicular to the grain boundary. The lines were spaced approximately 50 nanometers apart, to give an average of 30 points per image. At each intersection of the lines with the grain boundary, the β phase thickness was measured perpendicular to the precipitate. The continuity of the β phase was based on the presence or absence of the phase at the intersection point. Figure 6 shows an example of a micrograph overlayed with lines.

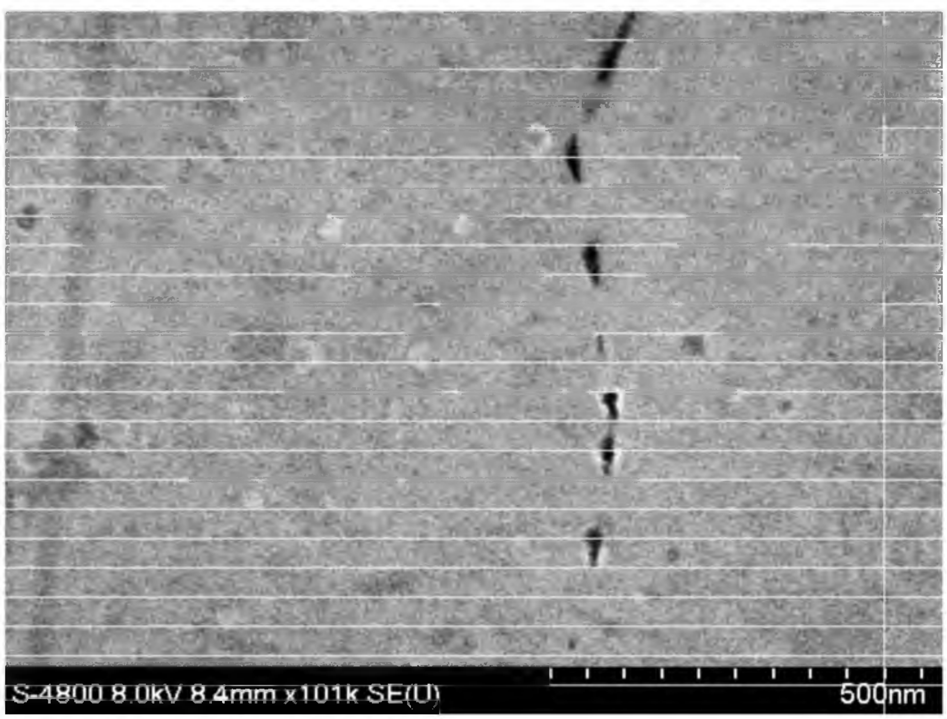

Figure 6 – Overlayed SEM micrograph of 5083-H131 sensitized at 70 °C for 12 months

4 RESULTS

4.1 Nitric Acid Mass Loss Testing

NAMLT standard tests were performed on all evaluated sensitized samples at a constant sensitization time of 12 months with three different sensitization temperatures, 50, 60, and 70 °C, respectively. In addition, NAMLT results for a single sample, 5083-H131, were collected for samples at the same sensitization temperature and different sensitization times. The results of these tests can be seen in Table 5.

In addition, variations of the standard ASTM G67 were run at higher nitric acid temperatures, 50 °C, for two samples, 5083-H131 and 5456-H116. The mass loss results of these tests compared with those of the standard tests for the same sensitized sample can be found in Table 6.

Further analysis of these data was completed to evaluate the controlling step in aluminum matrix and β phase dissolution during NAMLT by plotting the natural log of the mass loss against the inverse of the temperature, as seen in Figure 7. Based on the slope of these curves, estimations of the activation energy for the reaction of nitric acid with the various samples were calculated, as shown in Table 7.

Table 5 – Standard NAMLT test results [59]

Aluminum Alloy	Sensitization Temperature (°C)	Sensitization Time (Months)	Mass Loss (mg/cm2)
5083-H131	70	3	33.5
5083-H131	70	6	37.1
5083-H131	70	24	45.4
5083-H131	70	30	41.6
5083-H131	70	12	43.0
5083-H131	60	12	32.5
5083-H131	50	12	22.2
5083-H321	70	12	45.0
5083-H321	60	12	32.6
5083-H116	70	12	40.0
5083-H116	60	12	30.9
5083-H116	50	12	11.3
5456-H116	70	12	45.0
5456-H116	60	12	37.1
5456-H116	50	12	31.0

Table 6 – 50 °C NAMLT results

Alloy	Sensitization Temperature (°C)	Sensitization Time (hrs)	NAMLT Temperature (°C)	Mass Loss (mg/cm^2)
5083-H131	150	120	50	304.9
5083-H131	150	120	30	40.9
5083-H131	150	2.5	50	175.4
5083-H131	150	2.5	30	17.7
5083-H131	N/A	0	50	66.4
5083-H131	N/A	0	30	5.1
5456-H116	60	12960	50	234
5456-H116	60	12960	30	37

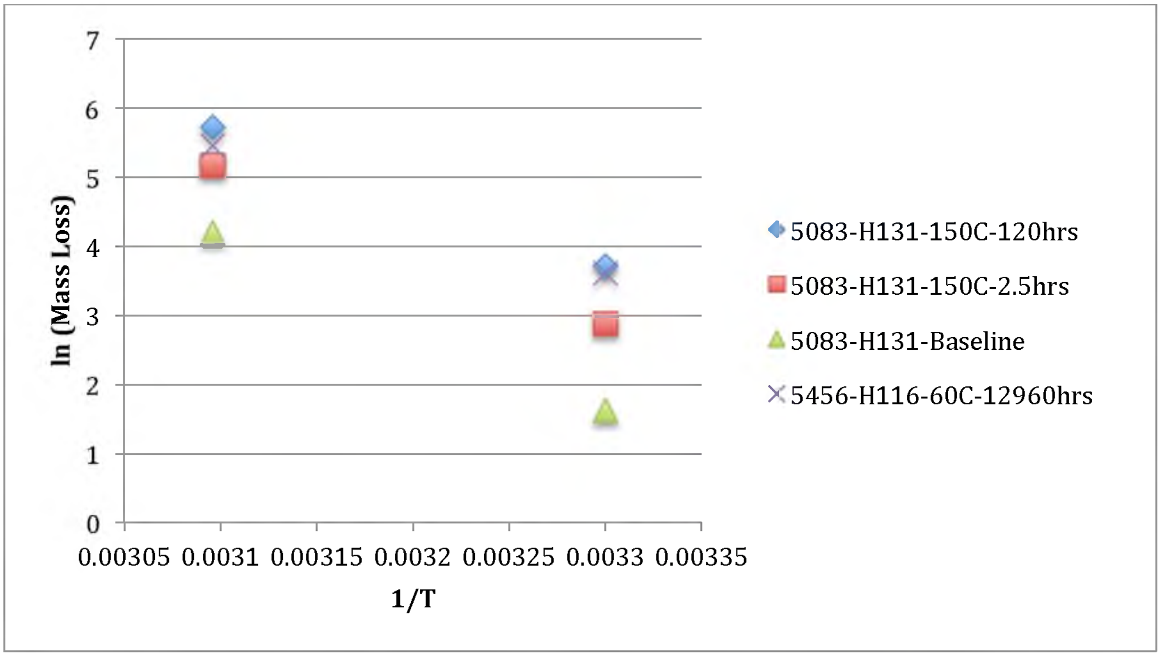

Figure 7 – Ahrenius plot for the various samples tested

Table 7 – Activation energies

Alloy	Sensitization Temperature (°C)	Sensitization Time (hrs)	Activation Energy (kJ/mol)
5083-H131	150	120	81.7
5083-H131	150	2.5	93.3
5083-H131	N/A	0	104.4
5456-H116	60	12960	75.0

As is apparent from the data in Table 7, both the β phase dissolution rate and the aluminum matrix reaction rate with the nitric acid are high, with activation energies well above the typical threshold value of 25 kJ/mol for diffusion through liquids, thereby suggesting reaction control. [58] In addition, there is a significant drop in the activation energy of around 20-25 kJ/mol in the fully sensitized samples of 5083-H131-150C-120hrs and the 5456-H116-60C-12960hrs when compared with the unsensitized sample of 5083-H131. Therefore, the nitric acid dissolution rate of the β phase is much higher than the reaction rate of nitric acid with the aluminum matrix, as would be expected. The intermediately sensitized sample of 5083-H131-150C-2.5hrs showed an activation energy between the values of the fully sensitized and unsensitized samples showing a contributing influence of both reaction rates to the effective overall rate for the sample. The results are consistent with previous understanding of sensitization and the ASTM G67 test results. These tests were used to qualitatively determine the rate-controlling factor of this system. The high values of the estimated activation energies for all the samples studied leads to the conclusion that the reactions in questions, the dissolution of the both the aluminum matrix and the β phase, are reaction controlled steps not diffusion controlled steps.

Another variation on the standard NAMLT involved investigations into the effect of variations in hydrogen ion or acid concentration on the mass loss results. For a single sample, the concentration of the nitric acid was varied from 7% up to typical concentrated nitric acid or 70%. Table 8 shows the results. These results

Table 8 – Mass loss results from varying nitric acid concentrations

Alloy	Sensitization Temperature (°C)	Sensitization Time (hrs)	NAMLT Nitric Acid Concentration (%)	Mass Loss (mg/cm2)
5083-H131	60	12960	70	38.5
5083-H131	60	12960	46.7	127.4
5083-H131	60	12960	23.3	137.3
5083-H131	60	12960	7	73.9

were analyzed through a log-log plot in order to evaluate the reaction order with respect to hydrogen ion or acid concentration. Figure 8 shows a lack of typical reaction order kinetics for the nitric acid-aluminum system under investigation. Traditional simple reaction kinetics breaks down for the system, presumably due to electrochemical and passivation factors inherent in the materials.

4.2 Atomic Force Microscopy

The initial etching rates of both the nitric and phosphoric acids are shown in Table 9 and Table 10, respectively. Both the widening rate and the depth penetration rate are shown. Examples of the AFM images and depth plots for both acids are shown in Figure 9 through Figure 16.

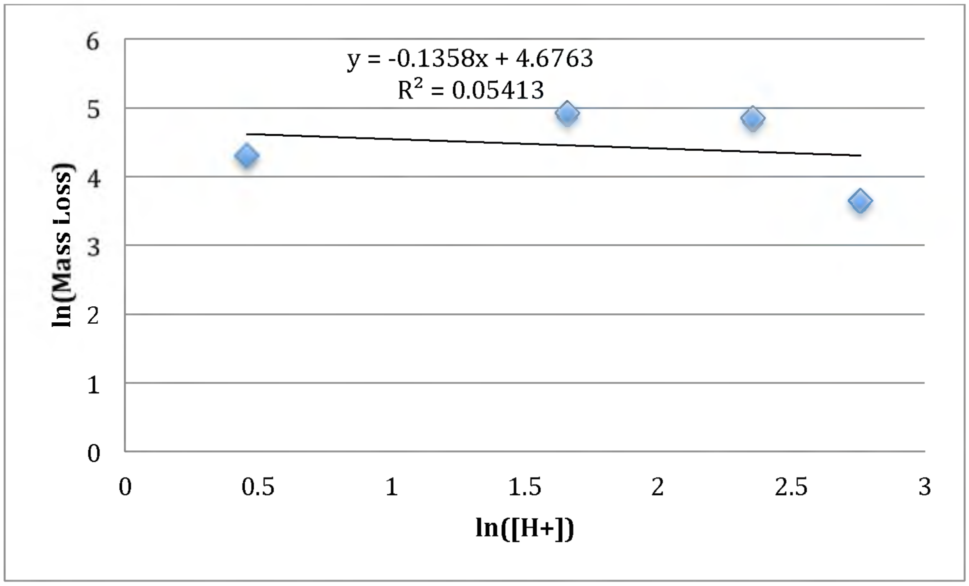

Figure 8 – Reaction order plot for NAMLT

Table 9 – Nitric acid etch rates

Nitric Acid				
Area	Initial Width Rate (nm/s)	Standard Deviation	Initial Depth Rate (nm/s)	Standard Deviation
Grain Boundary	5.7	0.5	0.063	0.005
Pre/Thin	6.8	0.2	0.113	0.009
Beta	9.3	1.5	0.3	0.1

Table 10 – Phosphoric acid etch rates

Phosphoric Acid				
Area	Initial Width Rate (nm/s)	Standard Deviation	Initial Depth Rate (nm/s)	Standard Deviation
Grain Boundary	0.106	0.008	0.014	0.004
Pre/Thin	0.22	0.02	0.04	0.02
Beta	2.1	0.1	0.13	0.03

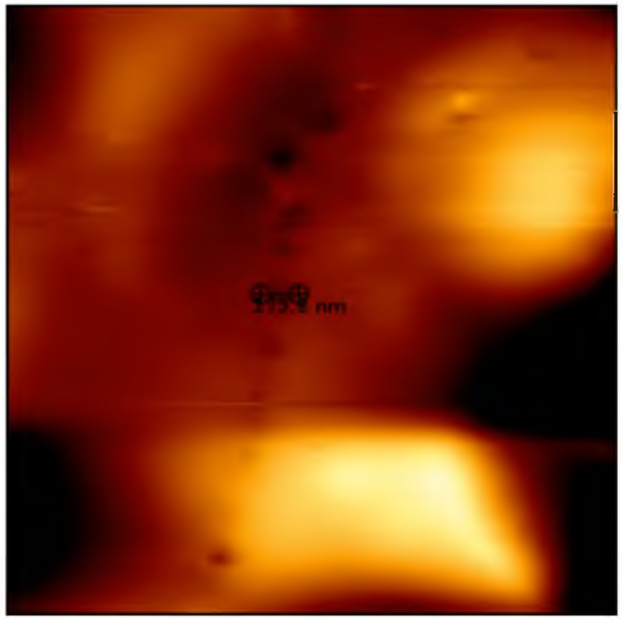

Figure 9 – AFM image of a β phase particle after 15-second etch in nitric acid

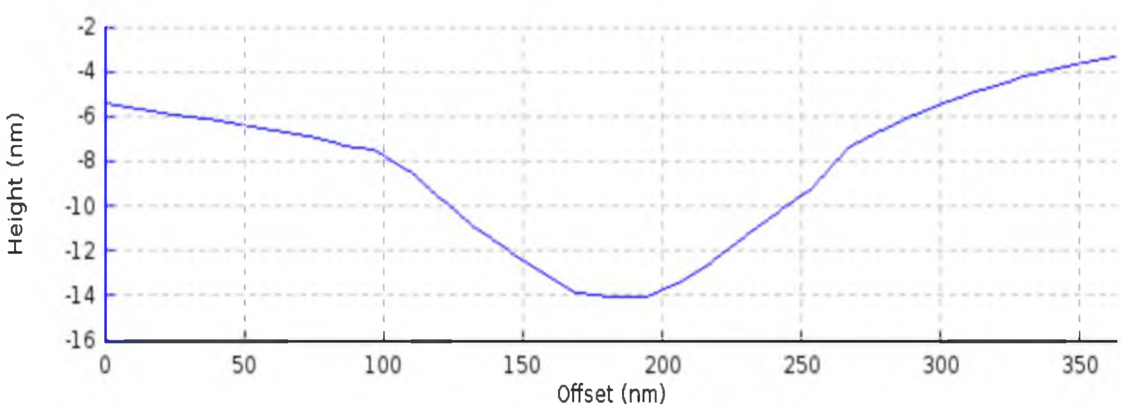

Figure 10 – Depth plot of a β phase particle after 15-second etch in nitric acid

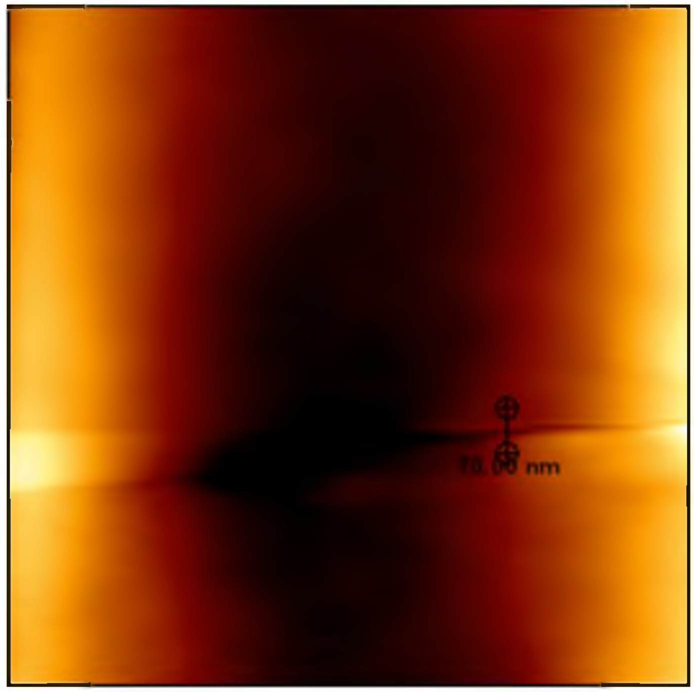

Figure 11 – AFM image of a pre/thin β phase after 90-second etch in phosphoric acid

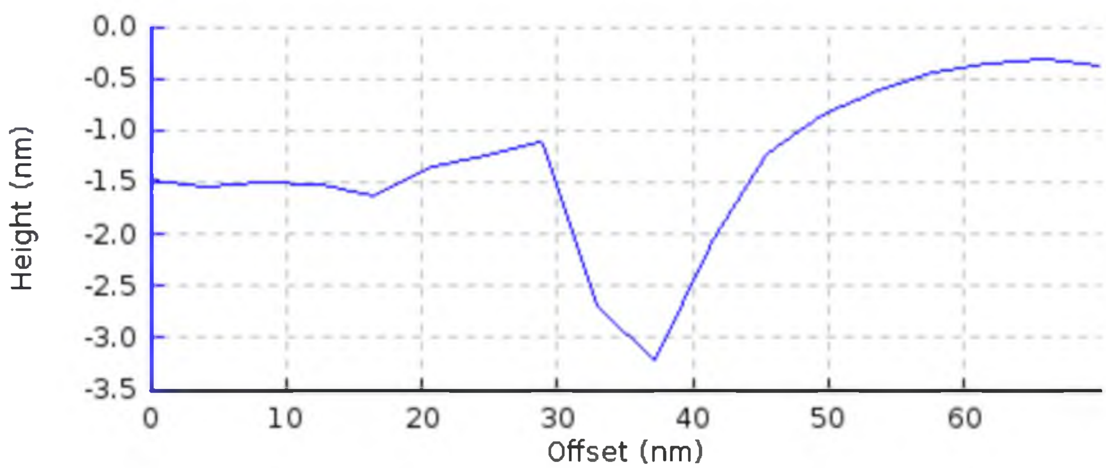

Figure 12 – Depth plot of pre/thin β phase after 90-second etch in phosphoric acid

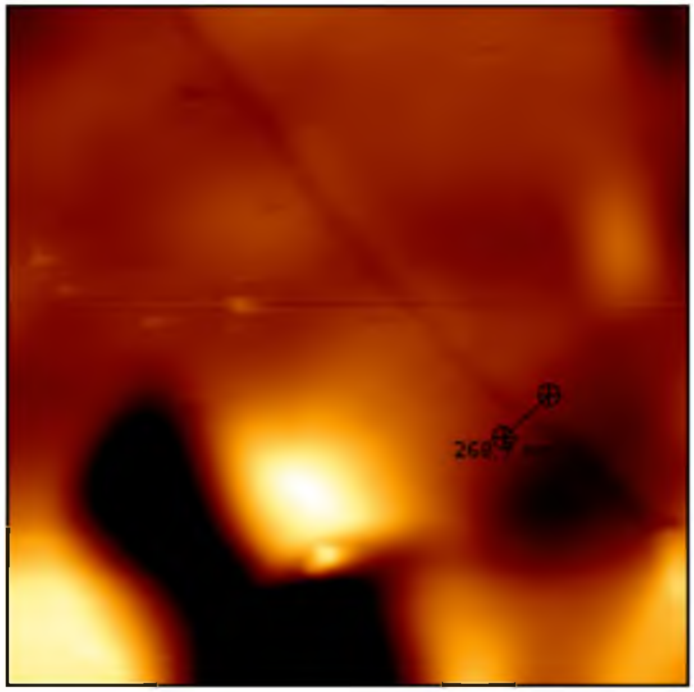

Figure 13 – AFM image of a pre/thin β phase after 15-second etch in nitric acid

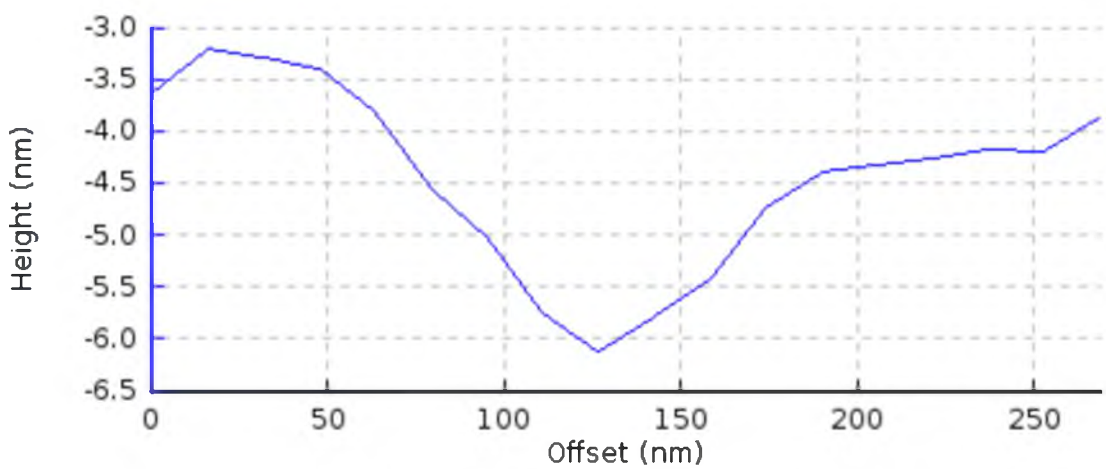

Figure 14 – Depth plot of pre/thin β phase after 15-second etch in nitric acid

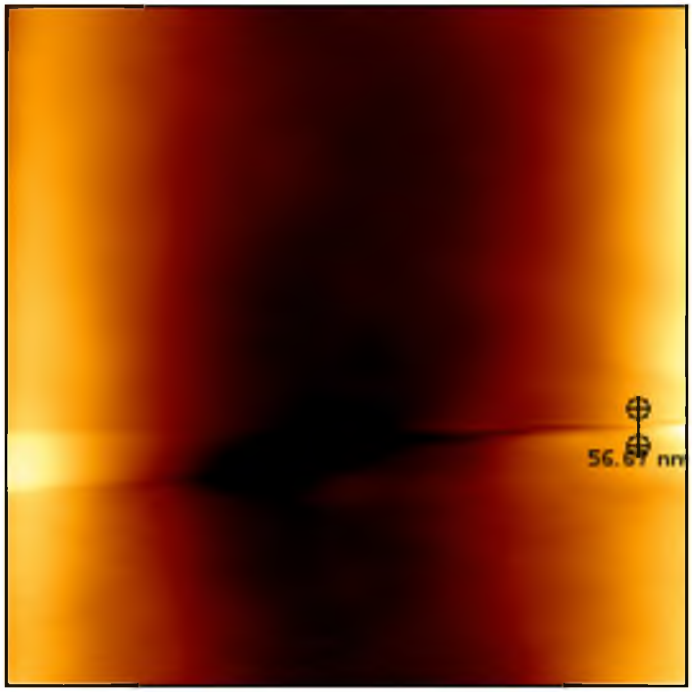

Figure 15 – AFM image of a grain boundary after 90-second etch in phosphoric acid

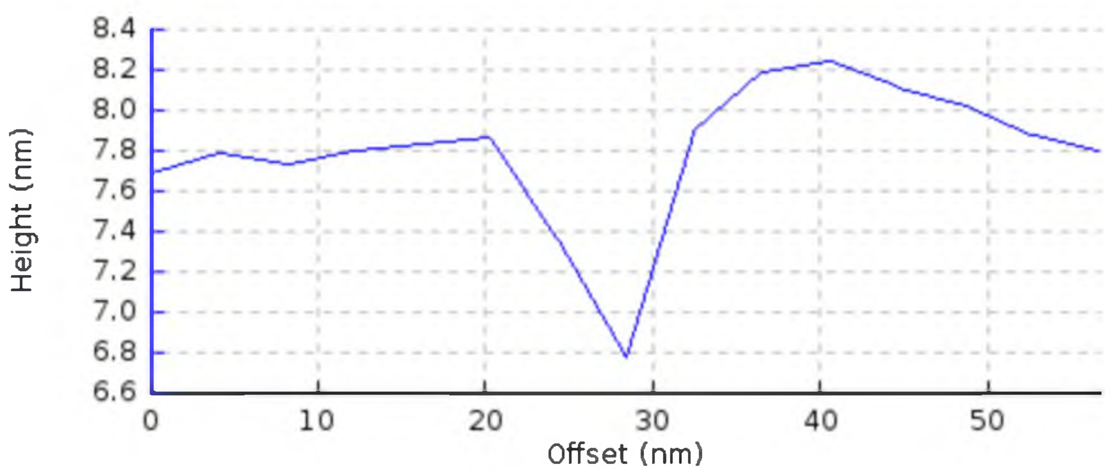

Figure 16 – Depth plot of a grain boundary after 90-second etch in phosphoric acid

4.3 Thickness and β Phase Measurement

From the SEM images, the β phase thickness measurements were put into various counting bins based on size. The percentage contribution of each bin or the number of measurements in a particular bin divided by the total overall number of counts was multiplied by the average thickness of a particular bin in order to give the thickness contribution of that bin. The thickness contributions were then summed over all the bins to give the average thickness of the β phase for a particular sample.

Table 11 shows the combined results for a single sample after analysis of all the images taken for that sample. Completing a similar analysis for all 4 samples types at the three temperatures of interest yielded the following charts, Figure 17 through Figure 20.

From Figure 17 through Figure 20, there is a clear trend of increasing β phase nictric acid etch penetration thickness as sensitization temperature increases for all four samples studied.

In addition, for a single sample, aluminum 5083-H131, measurements were taken for the same temperature at different sensitization times. The results for β phase thickness and continuity are shown in Figure 21 and Figure 22, respectively.

Table 12 shows the consolidated results of continuity and β phase thickness for all the samples studied, along with the corresponding mass loss test results.

Table 11 – SEM tabulated thickness and continuity for aluminum 5083-H116, Sensitized at 70 °C for 12 months [59]

5083-H116-70C-12Months				
Continuity	57.7%			
Thickness	Count	% Contribution	Bin Average Thickness	Thickness Contribution
0	703	42.3%	0	0.00
0-5	347	20.9%	2.5	0.52
5-10	441	26.6%	7.5	1.99
10-20	102	6.1%	15	0.92
20-30	36	2.2%	25	0.54
30-40	20	1.2%	35	0.42
40-50	3	0.2%	45	0.08
50-75	4	0.2%	62.5	0.15
75-100	2	0.1%	87.5	0.11
100-150	1	0.1%	125	0.08
150-200	0	0.0%	175	0.00
>200	2	0.1%	250	0.30
Total Count	1661		Total Thickness	5.11

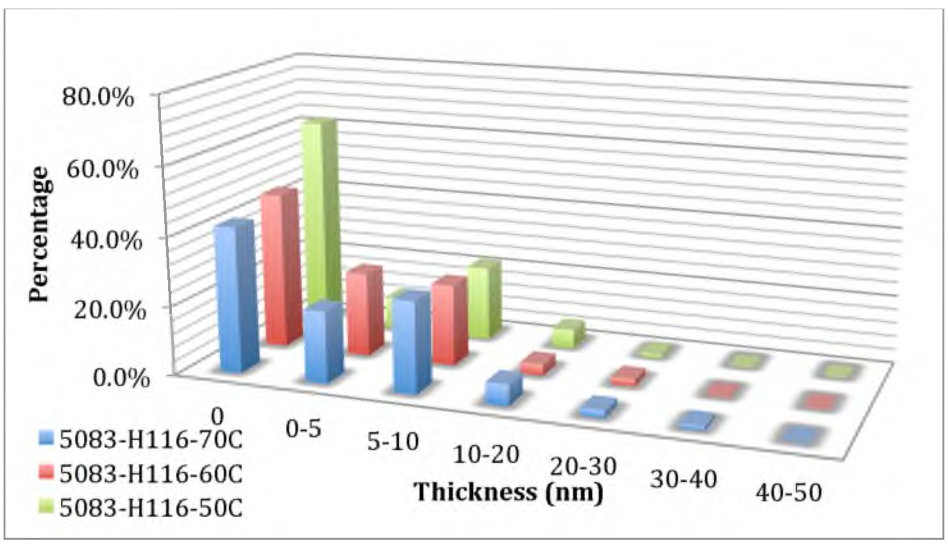

Figure 17 –Nitric acid etch penetration thickness measurements of aluminum 5083-H116 for sensitization at 50 °C, 60 °C, and 70 °C for 12 months, respectively

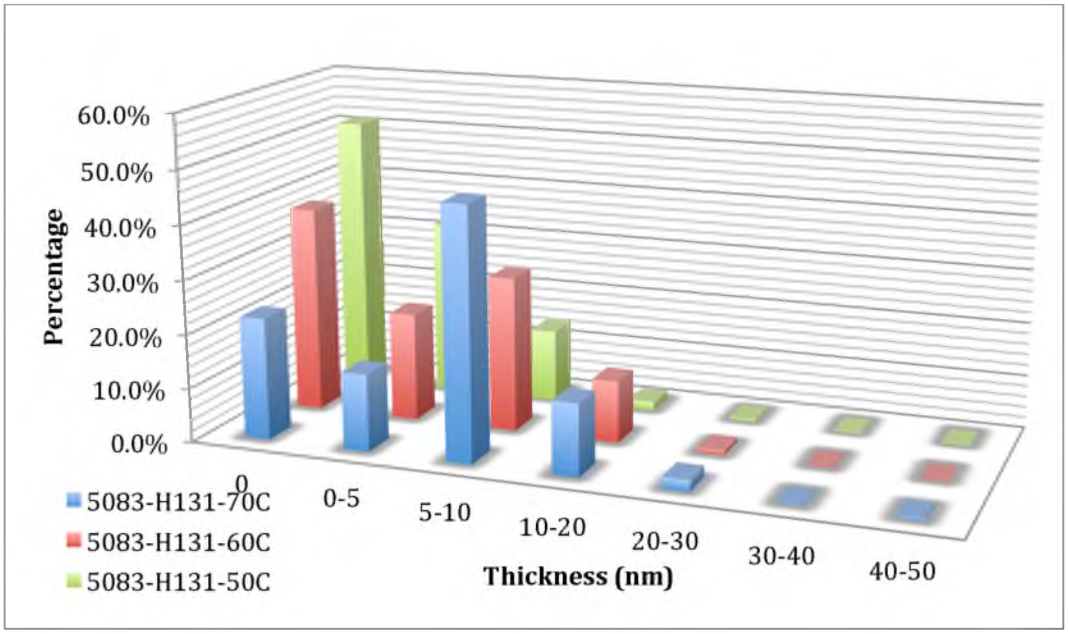

Figure 18 - Nitric acid etch penetration thickness measurements of aluminum 5083-H131 for sensitization at 50 °C, 60 °C, and 70 °C for 12 months, respectively

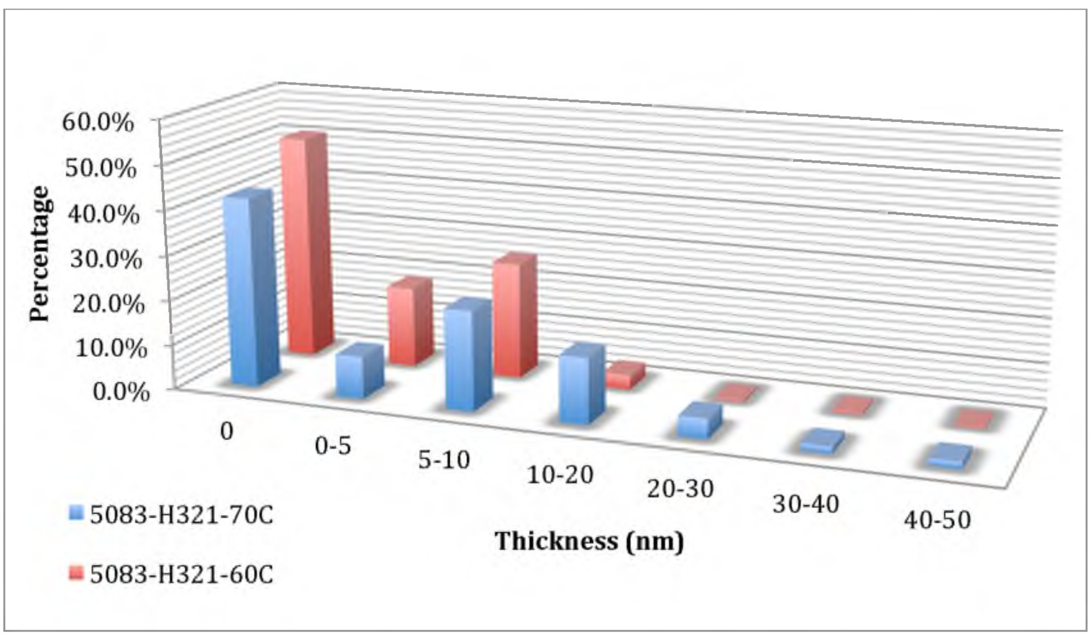

Figure 19 - Nitric acid etch penetration thickness measurements of aluminum 5083-H321 for sensitization at 60 °C and 70 °C for 12 months, respectively

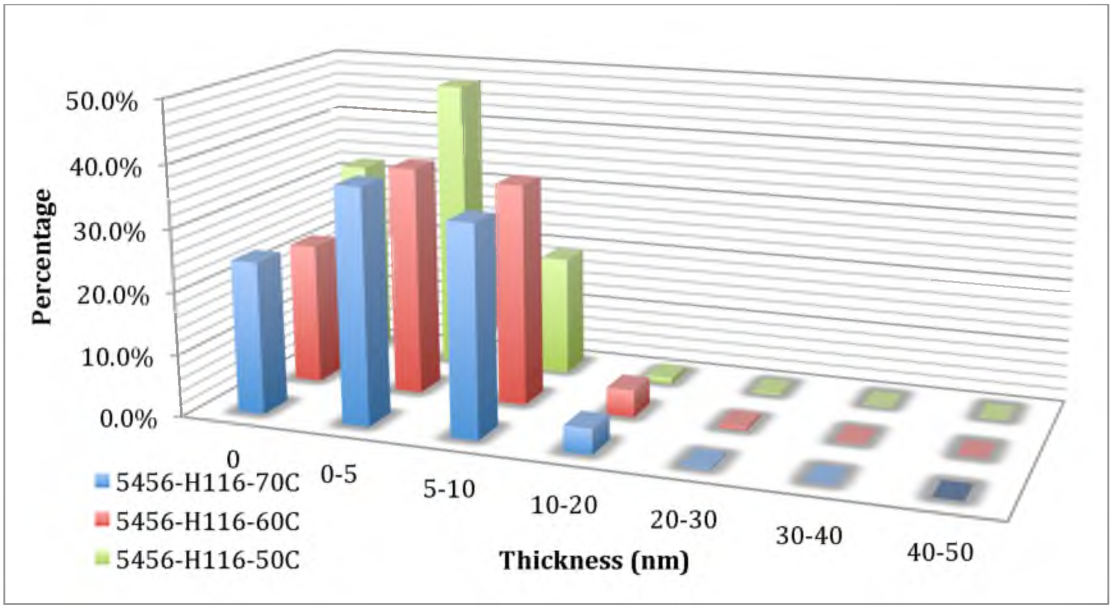

Figure 20 - Nitric acid etch penetration thickness measurements of aluminum 5456-H116 for sensitization at 50 °C, 60 °C, and 70 °C for 12 months, respectively

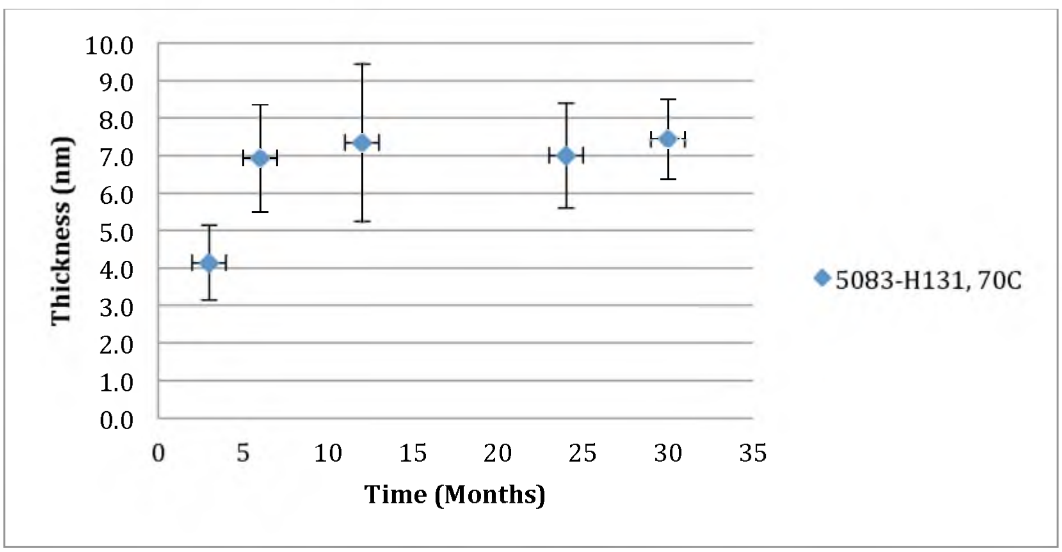

Figure 21 – β phase thickness versus sensitization time for aluminum 5083-H131 at 70 °C

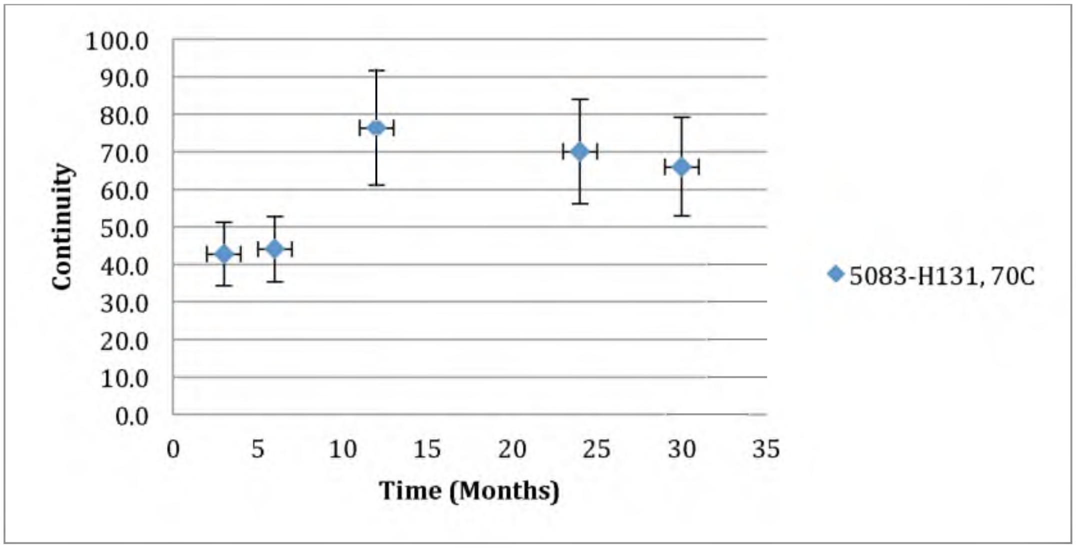

Figure 22 - β phase continuity versus sensitization time for aluminum 5083-H131 at 70 °C

Table 12 – Complete SEM imaging results [59]

Aluminum Alloy	Sensitization Temperature (°C)	Sensitization Time (Months)	β Phase Thickness (nm)	β Phase Continuity (%)	Mass Loss (mg/cm2)
5083-H131	70	3	4.1	42.7	33.5
5083-H131	70	6	6.9	44.0	37.1
5083-H131	70	24	7.0	70.0	45.4
5083-H131	70	30	7.4	66.0	41.6
5083-H131	70	12	7.3	76.4	43.0
5083-H131	60	12	4.4	61.6	32.5
5083-H131	50	12	3.0	48.8	22.2
5083-H321	70	12	10.2	54.3	45.0
5083-H321	60	12	4.1	49.4	32.6
5083-H116	70	12	5.4	54.8	40.0
5083-H116	60	12	4.3	54.3	30.9
5083-H116	50	12	2.7	37.9	11.3
5456-H116	70	12	5.3	75.6	45.0
5456-H116	60	12	4.2	77.3	37.1
5456-H116	50	12	4.0	67.7	31.0

5 MASS LOSS MODEL

5.1 Preliminary Models

Initially, several models were developed around defining the rate determining processes of the two main reactions that occur within the mass loss test, the dissolution of aluminum matrix along the grain boundary, and the dissolution of β phase precipitate along the grain boundary. Given the foundational knowledge of β phase precipitation and corrosion, it is known that the β phase precipitates corrode more quickly than the aluminum matrix along the grain boundary. Therefore the initial model assumed a reaction dominated step of aluminum matrix dissolution with a diffusion controlled step of β phase dissolution.

Beginning with the diffusion controlled step for β phase dissolution, Ficks first law, shown in Equation 2, was taken as the governing equation, given the net change in the concentration of the hydrogen ion in the acid was minimal. The loss was estimated at less than 1%, assuming complete β phase coverage at 50 nm thickness, 10 um grain size and a consumption of 3 moles of hydrogen per mole of aluminum

$$J = D' \frac{dC}{dx}$$ Equation 2

where J is the flux of hydrogen ions into the sample, D' is the effective diffusion coefficient of the hydrogen, C is the hydrogen concentration and x is the distance into the sample from the surface.

The flux of hydrogen ions into the aluminum sample is defined as:

$$J = \frac{N_{H^+}}{At}$$ Equation 3

where N_{H^+} is the number of moles of hydrogen that react with the β phase, A is the area of penetration and t is the time.

The area of penetration can be further defined as:

$$A = \pi\, G\, S$$ Equation 4

where G is the average grain size and S is the β phase thickness.

Furthermore, the number of moles of hydrogen reacted with the β phase can be correlated with the number of moles of aluminum in the β phase that are removed from the material, as shown in Equation 5:

$$N_{H^+} = \frac{N_{Al}}{3} = \frac{\pi\, G\, S\, d\, \rho_{Al}}{3\, MM_{Al}}$$ Equation 5

where N_{Al} is the number of moles of aluminum removed, *d* is the total penetration depth into the sample, ρ_{Al} and MM_{Al} are the density and molar mass of the sample respectively. Combining Equation 3, Equation 4, and Equation 5, the flux of hydrogen ions is defined as:

$$J = \frac{d\, \rho_{Al}}{3\, MM_{Al} t}$$ Equation 6

Setting Equation 2 and Equation 6 equal gives:

$$\frac{d\,\rho_{Al}}{3\,MM_{Al}t} = D'\frac{(C_b - 0)}{d} \qquad \text{Equation 7}$$

where C_b is the bulk hydrogen concentration in the nitric acid.

Solving for the overall penetration depth d gives:

$$d = \sqrt{\frac{3\,D'C_b\,MM_{Al}\,t}{\rho_{Al}}} \qquad \text{Equation 8}$$

with the definition of mass loss, ML, shown in Equation 9, the mass loss due to the presence of the β phase can be seen in Equation 10.

$$ML_{\beta} = \frac{Mass\ Lost}{A} = \frac{\Phi\,A\,d\,\rho_{Al}}{A} \qquad \text{Equation 9}$$

$$ML_{\beta} = \Phi\,\rho_{Al}\sqrt{\frac{3\,D'C_b MM_{Al}t}{\rho_{Al}}} \qquad \text{Equation 10}$$

Due to the narrow channels through which the hydrogen must diffuse, the effective diffusion coefficient was defined using Renkin diffusion, which was developed for diffusion through a small pore. Renkin adjusts the diffusion coefficient through a narrow channel based on the ratio between the radius of the solute ion and the pore radius. The form of Renkin diffusion is shown in Equation 11.

$$D' = D_{H^+}\,(1 - 2.104\left(\frac{R}{S}\right) + 2.09\left(\frac{R}{S}\right)^3 - 0.956\left(\frac{R}{S}\right)^5)^{0.5} \qquad \text{Equation 11}$$

where R is the radius of the solute ion, S is the radius of the pore, and D_{H^+} is the hydrogen diffusion coefficient in free liquid.

Combining this effect, as well as all of the constants into a single variable, shown in Equation 12, the final mass loss contribution due to the presence of β phase precipitates along the grain boundary can be seen in Equation 13.

$$\alpha = \Phi\ \sqrt{3\, D_{H^+}\, C_b\, MM_{Al}\, t\, \rho_{Al}} \qquad \text{Equation 12}$$

$$ML_{\boldsymbol{\beta}} = \alpha\ (1 - 2.104\left(\frac{R}{S}\right) + 2.09\left(\frac{R}{S}\right)^3 - 0.956\left(\frac{R}{S}\right)^5)^{0.5} \qquad \text{Equation 13}$$

In addition, the reaction of the nitric acid with the aluminum matrix along the grain boundary also has an effect on the overall mass loss. To determine this, the basic rate form, shown in Equation 14, was taken as the starting point, assuming for simplicity a reaction order of one with respect to the hydrogen concentration:

$$\frac{dC_{H^+}}{dt} = k_{\mathbf{H}^+} C_{H^+}(t) \qquad \text{Equation 14}$$

where $C_{H^+}(t)$ is the concentration of the hydrogen ion in the bulk solution at time t and $k_{\mathbf{H}^+}$ is the reaction constant.

Solving this equation for the hydrogen concentration gives Equation 15:

$$C_{H^+}(t) = C_1 e^{k_{\mathbf{H}^+} t} \qquad \text{Equation 15}$$

where C_1 is a constant. As discussed previously, this assumes no depletion of the hydrogen ion in solution. Given the initial condition, shown in Equation 16, this constant is then specified as C_b or the initial bulk concentration of the hydrogen ion in the nitric acid.

$$C_{H^+}(0) = C_b \rightarrow\ C_1 = C_b \qquad \text{Equation 16}$$

Based on the stoichiometric relationship, the change in concentration of hydrogen ions directly correlates with the presence of dissolved aluminum in the solution, given in Equation 17.

$$C_{Al}(t) = \frac{\Delta C_{H^+}(t)}{3} \qquad \text{Equation 17}$$

Combining Equation 15 and Equation 17 yields Equation 18 or the concentration of aluminum with respect to time.

$$C_{Al}(t) = \frac{C_b - C_{H^+}(t)}{3} = \frac{C_b}{3}\left(1 - e^{k_{\mathrm{H}^+} t}\right) \qquad \text{Equation 18}$$

The concentration of aluminum can also be related to the depth of penetration of the nitric acid into the sample and the corresponding quantity of aluminum dissolved by the reaction, shown in Equation 19:

$$C(t) = \frac{2\,\pi\,\mathrm{G}\,\mathrm{T}\prime\,\mathrm{d}\,\rho_{Al}\,\#G}{2\,MM_{Al}\,V} \qquad \text{Equation 19}$$

where G is the average grain size, T′ is the thickness of the grain boundary, d is the penetration depth, ρ_{Al} is the aluminum density, $\#G$ is the number of grain layers, MM_{Al} is the molar mass of the aluminum, and V is the volume of the nitric acid solution. Combining Equation 18 and Equation 19 leads to Equation 20.

$$\frac{C_b}{3}\left(1 - e^{k_{\mathrm{H}^+} t}\right) = \frac{\pi\,\mathrm{G}\,\mathrm{T}\prime\,\mathrm{d}\,\rho_{Al}\,\#G}{MM_{Al}\,V} \qquad \text{Equation 20}$$

Equation 20 can be rearranged to solve for the depth of penetration.

$$d_{Al} = \frac{C_b\,MM_{Al}\,V}{3\,\pi\,\mathrm{G}\,\mathrm{T}\prime\,\rho_{Al}\,\#G}\left(1 - e^{k_{\mathrm{H}^+} t}\right) \qquad \text{Equation 21}$$

Combining Equation 21 with Equation 9 yields the final result for the mass loss contribution due to the dissolution of the aluminum matrix along the grain boundary.

$$ML_{\mathbf{Al}} = \frac{C_b\,\Phi\,MM_{Al}\,V}{3\,\pi\,\mathrm{G}\,\mathrm{T}\prime\,\#G}\left(1 - e^{k_{\mathrm{H}^+} t}\right) \qquad \text{Equation 22}$$

Consolidating the constants in Equation 22 simplifies the result further.

$$\sigma = \frac{C_b\,\Phi\,MM_{Al}\,V}{3\,\pi\,\mathrm{G}\,\#G} \qquad \text{Equation 23}$$

$$ML_{\mathbf{Al}} = \frac{\sigma}{\mathrm{T}\prime}\left(1 - e^{k_{\mathrm{H}^+} t}\right) \qquad \text{Equation 24}$$

Combining the effects of both aluminum matrix reaction and β phase dissolution is weighted based on the percentage of β phase present or the continuity, θ, shown in Equation 25.

$$ML_{Total} = (1-\theta)\, ML_{\mathbf{Al}} + \theta\, ML_{\boldsymbol{\beta}} \qquad \text{Equation 25}$$

This yields the overall result of the mass loss given in Equation 26.

$$ML_{Total} = (1-\theta)\,\frac{\sigma}{T'}\left(1-e^{k_{\mathrm{H}^+}t}\right) + \theta\,\alpha \left(1-2.104\left(\frac{R}{S}\right)+2.09\left(\frac{R}{S}\right)^3-0.956\left(\frac{R}{S}\right)^5\right)^{0.5} \qquad \text{Equation 26}$$

The predicted mass loss based on thickness is shown in Figure 23.

A comparison between the model prediction and the actual results of the mass loss experiments, shown in Figure 24, demonstrations that the model provides a reasonable description of the mass loss. A revision on this model was undertaken

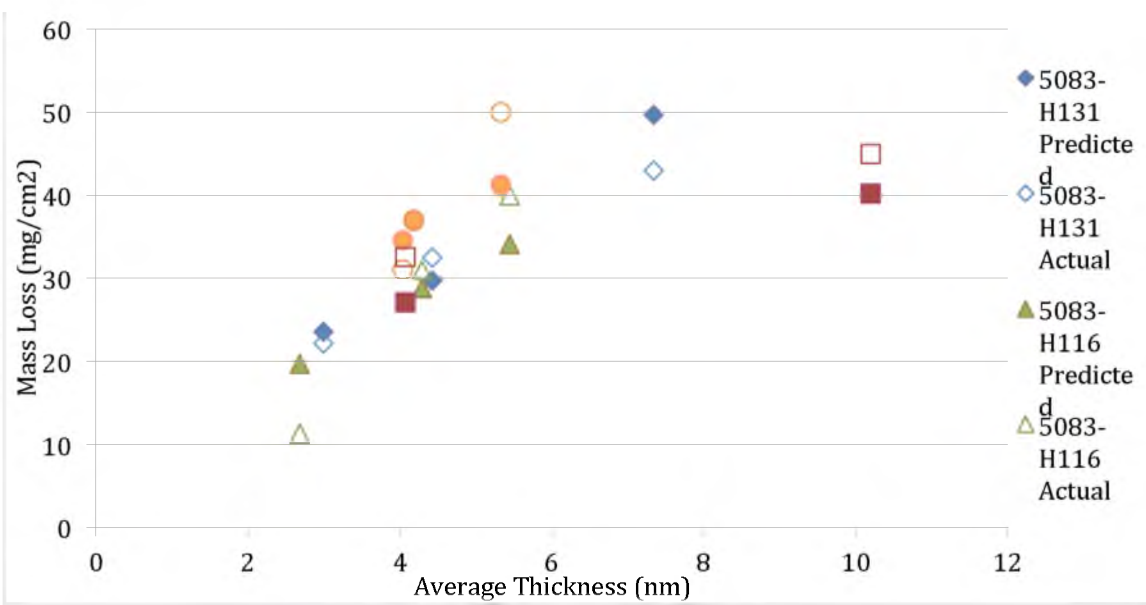

Figure 23 – Diffusion-reaction model comparison

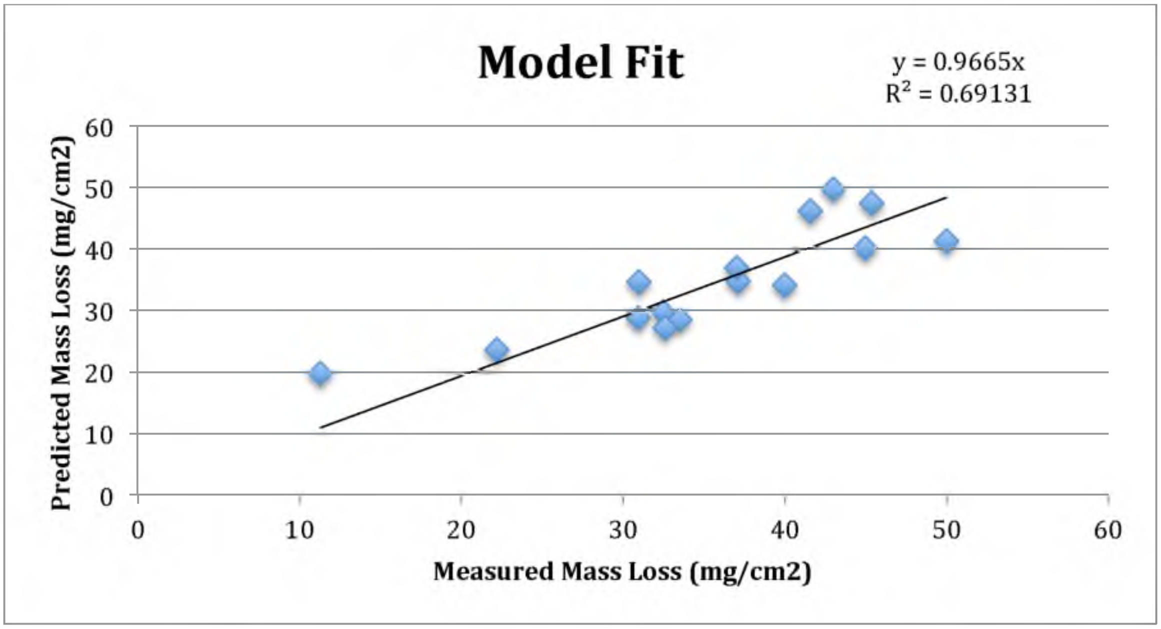

Figure 24 – Diffusion-reaction model fit

once it became apparent through further testing that both the matrix and β phase dissolution were reaction controlled. For this revision, the previous work undertaken on the matrix reaction portion was retained, and the final result is shown in Equation 24. The β phase diffusion portion, however, was re-derived using a similar methodology, beginning with the results from Equation 18. This is shown again as Equation 27 for the β phase reaction replacing the matrix reaction constant with the β phase constant, k'_{H^+}.

$$C_{Al}(t) = \frac{C_b - C_{H^+}(t)}{3} = \frac{C_b}{3}\left(1 - e^{k'_{H^+}t}\right) \qquad \text{Equation 27}$$

As with the matrix reaction, the concentration of aluminum can also be related to the depth of penetration of the nitric acid into the sample and the corresponding quantity of aluminum dissolved by the reaction. This takes a slightly different form for the β phase dissolution, which is shown in Equation 28:

$$C(t) = \frac{2\,\pi\ \mathrm{G\,d}\,\rho_{Al}\,\#G}{2\,MM_{Al}\,V} \qquad \text{Equation 28}$$

where G is the average grain size, S is the β phase thickness along the grain boundary, d is the penetration depth, ρ_{Al} is the aluminum density, $\#G$ is the number of grain layers, MM_{Al} is the molar mass of the aluminum, and V is the volume of the nitric acid solution. Combining Equation 27 and Equation 28 leads to Equation 29.

$$\frac{C_b}{3}\left(1 - e^{k'_{H^+}t}\right) = \frac{\pi\,\mathrm{G\,S\,d}\,\rho_{Al}\,\#G}{MM_{Al}\,V} \qquad \text{Equation 29}$$

Equation 29 can be rearranged to solve for the depth of penetration.

$$d_{\beta} = \frac{C_b\,MM_{Al}\,V}{3\,\pi\,\mathrm{G\,S}\,\rho_{Al}\,\#G}\left(1 - e^{k'_{H^+}t}\right) \qquad \text{Equation 30}$$

With the same definition of the mass loss as shown in Equation 9, the mass loss due to the reaction with the β phase becomes;

$$ML_{\boldsymbol{\beta}} = \frac{C_b\,\Phi\,MM_{Al}\,V}{3\,\pi\,\mathrm{G\,S}\,\#G}\left(1 - e^{k'_{H^+}t}\right) \qquad \text{Equation 31}$$

As before, the constants can be consolidated into a single constant and the final result simplified.

$$\sigma = \frac{C_b\,\Phi\,MM_{Al}\,V}{3\,\pi\,\mathrm{G}\,\#G} \qquad \text{Equation 32}$$

$$ML_{\boldsymbol{\beta}} = \frac{\sigma}{\mathrm{S}}\left(1 - e^{k'_{H^+}t}\right) \qquad \text{Equation 33}$$

As with the β phase diffusion coefficient, the reaction rate constant will be affected by the thickness of the β phase. Using the same form as that of Renkin diffusion, the effective reaction constant can be shown as in Equation 34.

$$k'_{H^+} = k_\beta \left(1 - 2.104\left(\frac{R}{S}\right) + 2.09\left(\frac{R}{S}\right)^3 - 0.956\left(\frac{R}{S}\right)^5\right) \qquad \text{Equation 34}$$

Substituting Equation 34 into Equation 33 and utilizing Equation 25, the combined result assuming a reaction controlled step for both matrix and β phase dissolution is shown in Equation 35. The predicted mass loss of the sample based on thickness is shown in Figure 25 with the corresponding fit shown in Figure 26.

$$ML_{Total} = (1-\theta)\frac{\sigma}{T'}\left(1 - e^{k_{\mathrm{H}^+}t}\right) + \theta\frac{\sigma}{S}\left(1 - e^{k_\beta\left(1-2.104\left(\frac{R}{S}\right)+2.09\left(\frac{R}{S}\right)^3-0.956\left(\frac{R}{S}\right)^5\right)t}\right)$$

Equation 35

Unlike with the previously developed model, this model shows poor

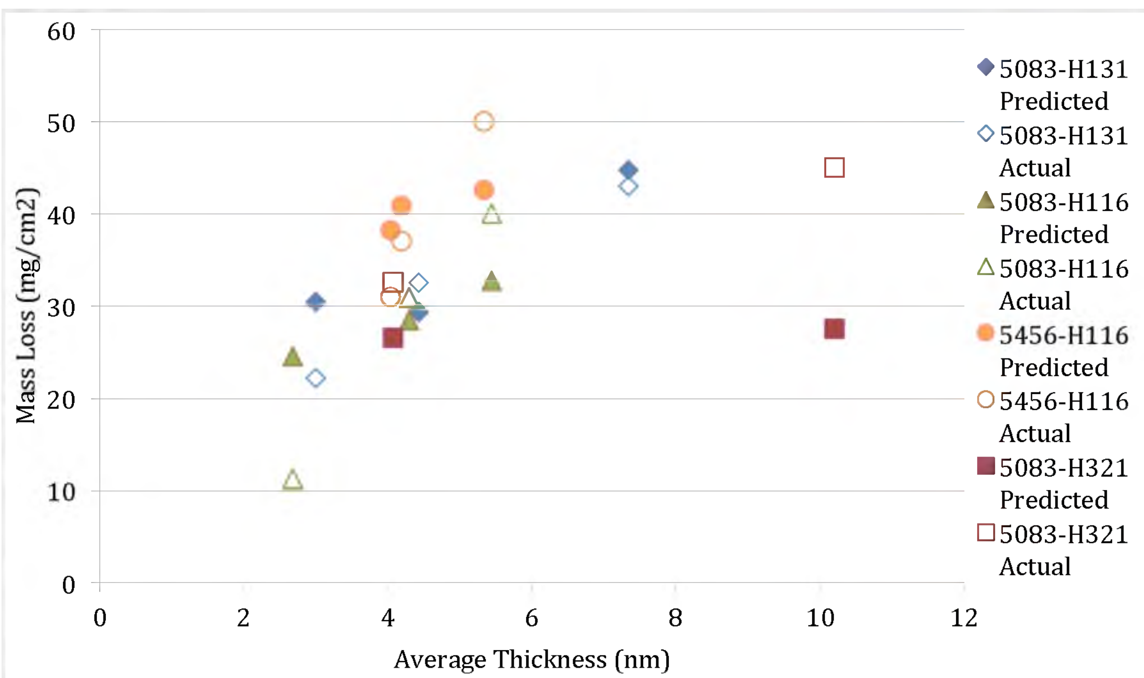

Figure 25 – Reaction-reaction model comparison

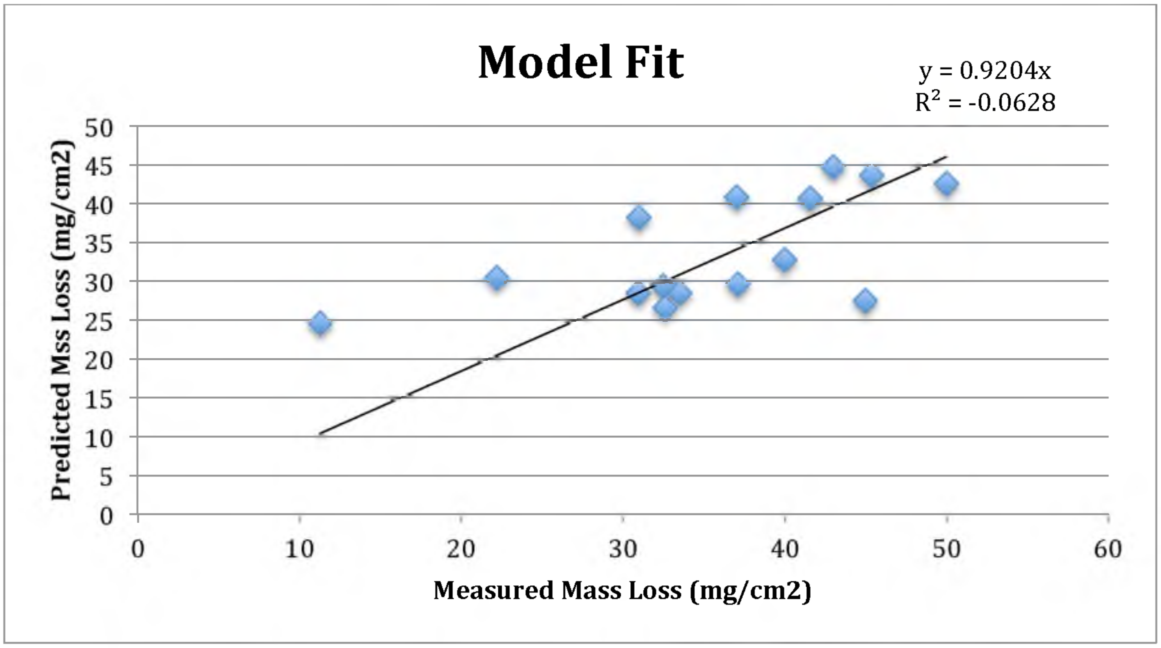

Figure 26 – Reaction-reaction model fit

comparison with the collected data. However, there are some steps in the derivation that lack rigorous fundamental backing. For instance, utilizing a Renkin style factor on the β phase dissolution rate constant is convenient and it is logical to suggest that the β phase dissolution rate increases with increase β phase thickness. More research would be needed in order to determine conclusively the form of this relationship, which is outside the scope of this work.

5.2 Model Development

The basis of the model begins with a definition of the quantity of mass that has been removed from the sample:

$$Mass\ Removed = \emptyset \rho_{Al} A d \qquad \text{Equation 36}$$

where Ø is the average penetration depth ratio , ρ_{Al} is the density of the bulk sample, A is the sample area and d is ultimate penetration depth. The average penetration depth ratio is based on the statistical nature of grain size distribution through the aluminum alloy. Given the ultimate mass loss of most samples around 50 mg/cm^2, the grain fallout depth can be estimated at approximately 185 um. From previous research, the average grain depth is around 340 um. [57] Since the typical grain is larger than the overall penetration depth, a grain will only experience fallout if the penetration can reach to the end of the grain. As such, there will be some grains that do not contribute to the mass loss, despite nitric acid penetration. Therefore, the penetration depth ratio accounts for the discrepancy between the ultimate penetration depth and the average depth to which grain fallout occurs. Based on Equation 36, the mass loss is then:

$$Mass\ Loss\ (ML) = \frac{Mass\ Removed}{A} = \emptyset\rho_{Al}d \qquad \text{Equation 37}$$

Equation 37 represents the general equation for the mass loss of the sample. The bulk density of aluminum is known and the average penetration depth ratio is defined as 0.5. The remaining unknown in Equation 37 is the penetration depth.

Analysis of the mass loss test provides the mathematical formulation for the penetration depth into the sample. Beginning with samples of completely continuous β phase or no β phase, the penetration depth is given by Equation 38:

$$d = Rt \qquad \text{Equation 38}$$

where R is the reaction or penetration rate into the sample and t is the time. Substitution of this general form into Equation 37 yields:

$$ML = \emptyset \rho_{Al} R t \quad \text{Equation 39}$$

Applying Equation 39 to the boundary conditions specified gives rise to the definition of two reaction or penetration rates, R_{Beta} and $R_{Grain\ Boundary\ (GB)}$:

$$R_{Beta} = \frac{ML_{Fully\ Sensitized}}{\emptyset \rho_{Al} t} \quad \text{Equation 40}$$

$$R_{GB} = \frac{ML_{Unsensitized}}{\emptyset \rho_{Al} t} \quad \text{Equation 41}$$

Both $ML_{Fully\ Sensitized}$ and $ML_{Unsensitized}$ are readily evaluated for any given sample and whose values are fairly consistent among the various 5000 series alloys. As such, these two rates are readily calculated for the alloys in question. However, although these two rates do accurately predict the mass loss in samples with complete β phase coverage and no β phase coverage, it is in the intermediate levels of β phase coverage where the majority of the predictions are needed.

Given the low exposure temperatures of these alloys in typical service conditions, as well as the test work carried out, it is reasonable that pre- β precipitates or thin β phase would exist, whose dissolution rate was not that of completely formed or thicker β phase. As such, a third reaction or penetration rate was introduced into the model to account for this phenomenon. Since the β phase precipitates preferentially grow along the grain boundary and given that pre- β phases or thin β phases would be logical precedents to that growth, the model assumes there is a ratio of the β phase length of either end of the precipitate, which is composed of the pre- β phase or thin β growth. A depiction of the model setup for a single β phase precipitate at a grain boundary can be seen in Figure 27.

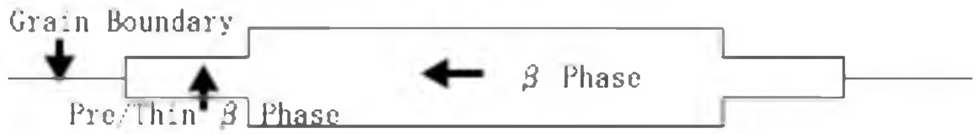

Figure 27 – Single β phase precipitate, phase 1

With this initial setup,Equation 39 can be used to describe the mass loss for the entire ASTM G67 test with a simple substitution of a single rate, with an overall effective rate, as seen in Equation 42.

$$ML = \emptyset \rho_{Al} R_{Effective} t \qquad \text{Equation 42}$$

This overall effective rate can be derived, based on the model setup shown in Figure 27. Taking the overall length as some arbitrary d_1, it can be shown that:

$$t_1 = \frac{(1-\theta-2x\theta)d_1}{R_{GB}} + \frac{2x\theta d_1}{R_{Pre}} + \frac{\theta d_1}{R_{Beta}} \qquad \text{Equation 43}$$

where t_1 is the time of penetration through this length, x is the pre- β /thin β fraction, θ is the β phase continuity, and R_{GB}, R_{Pre}, and R_{Beta} are the grain boundary, pre- β /thin β and full β phase reaction or penetration rates. The effective rate for this single β phase precipitate can then be found as:

$$R_{Effective} = \frac{d_1}{t_1} = \frac{1}{\frac{(1-\theta-2x\theta)}{R_{GB}} + \frac{2x\theta}{R_{Pre}} + \frac{\theta}{R_{Beta}}} \qquad \text{Equation 44}$$

$$R_{Effective} = \frac{R_{GB} R_{Pre} R_{Beta}}{(1-\theta-2x\theta) R_{Pre} R_{Beta} + 2x\theta R_{GB} R_{Beta} + \theta R_{GB} R_{Pre}}$$

Equation 45

Given that this $R_{Effective}$ was derived for an arbitrary β phase precipitate, it can be generalized as the overall effective reaction or penetration rate. Substituting

Equation 45 into Equation 42, gives the finalized form of the expression for the mass loss.

$$ML = \emptyset\rho_{Al}t\frac{R_{GB}R_{Pre}R_{Beta}}{(1-\theta-2x\theta)R_{Pre}R_{Beta} + 2x\theta R_{GB}R_{Beta} + \theta R_{GB}R_{Pre}}$$

Equation 46

As the continuity of the β phase along the grain boundary increases, there is a point at which the pre- β /thin β region surrounding one precipitate collides with this region surrounding another precipitate. When this occurs, the model setup shown in Figure 27 ceases to accurately depict the situation. Instead a new model setup must be used, as shown in Figure 28.

For this second phase that involves beta phase coalescence, Equation 42 still holds as the governing equation, however, a new effective reaction or penetration rate must be derived. Once again taking the overall length as some arbitrary d_1, it can be shown that:

$$t_1 = \frac{(1-\theta)d_1}{R_{Pre}} + \frac{\theta d_1}{R_{Beta}}$$ Equation 47

where t_1 is the time of penetration through this length, θ is the β phase continuity, and R_{Pre}, and R_{Beta} are the pre- β /thin β and full β phase reaction or penetration rates. The effective rate for this single β precipitate can then be found as:

$$R_{Effective} = \frac{d_1}{t_1} = \frac{1}{\frac{(1-\theta)d_1}{R_{Pre}} + \frac{\theta d_1}{R_{Beta}}} = \frac{R_{Pre}R_{Beta}}{(1-\theta)R_{Beta} + \theta R_{Pre}}$$

Equation 48

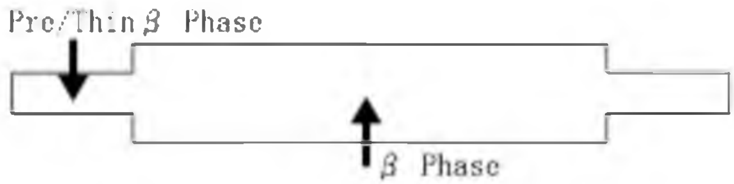

Figure 28 - Single β phase precipitate, phase 2

Once again this effective rate can be combined with Equation 42 to give the finalized form of the mass loss for phase 2.

$$ML = \emptyset \rho_{Al} t \frac{R_{Pre} R_{Beta}}{(1-\theta) R_{Beta} + \theta R_{Pre}} \quad \text{Equation 49}$$

Utilizing both Equation 46 and Equation 49, the mass loss of any level of β phase sensitization can be predicted. The transition point between phase 1 and 2 is readily defined as a specific continuity of the β phase.

$$Phase\ 1: \theta < \frac{100}{1+2x} \quad \text{Equation 50}$$

$$Phase\ 2: \theta \geq \frac{100}{1+2x} \quad \text{Equation 51}$$

Figure 29 shows the model fit for 0 to 100% β phase continuity. In order to validate the model predictions, the mass loss of several different aluminum 5000 series alloys, sensitized at temperatures ranging from 40-70 Celsius was measured. In addition, one dozen SEM micrographs were taken of grain boundaries in each sample to measure the β phase continuity. Figure 30 shows an example of one such image. Figure 31 and Figure 32 show comparisons of the model predicted mass loss to that of the measured mass loss. The data in both figures illustrates that there is a good correlation between the model predictions and actual

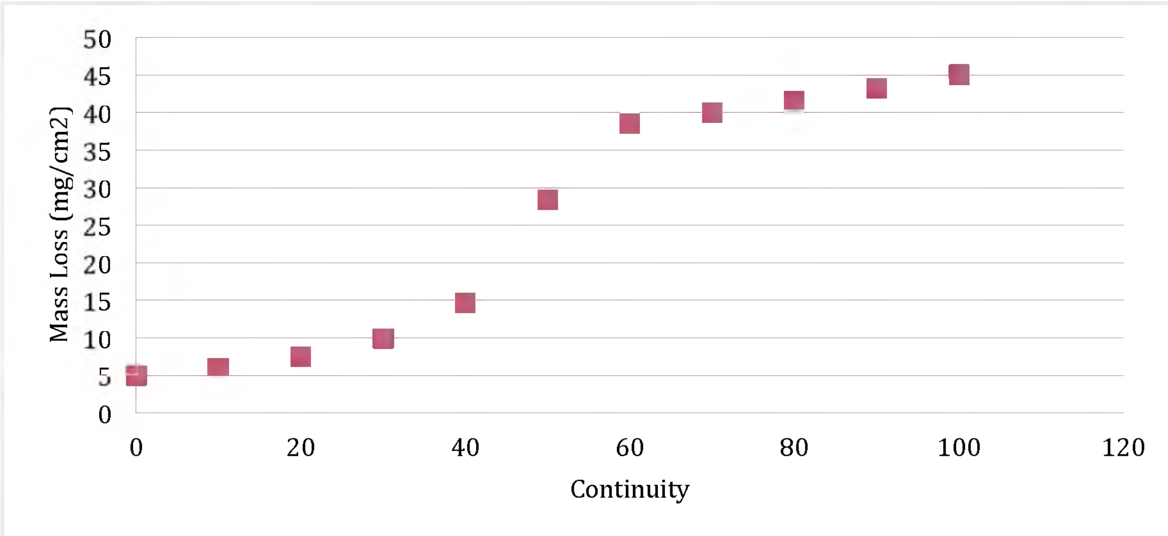

Figure 29 – Model mass loss predictions

measurements.

Based on the model, the main factor of the mass loss an Aluminum 5000 series alloy is that of β phase continuity within the sample. This makes logical sense, in that the more β phase precipitates along the grain boundary allows for a much faster penetration of the Nitric Acid into the sample, leading to more grain fallout and thus mass loss.

Given that the β phase continuity is the unknown variable in Equation 46 and Equation 49, these models are only useful when the β phase continuity within a sample can be predicted, knowing the sample characteristics, exposure time and temperature, and other important parameters. A corresponding model for the growth of grain boundary β phase precipitates has been developed, taking into account these various parameters, whose output gives the continuity of the β

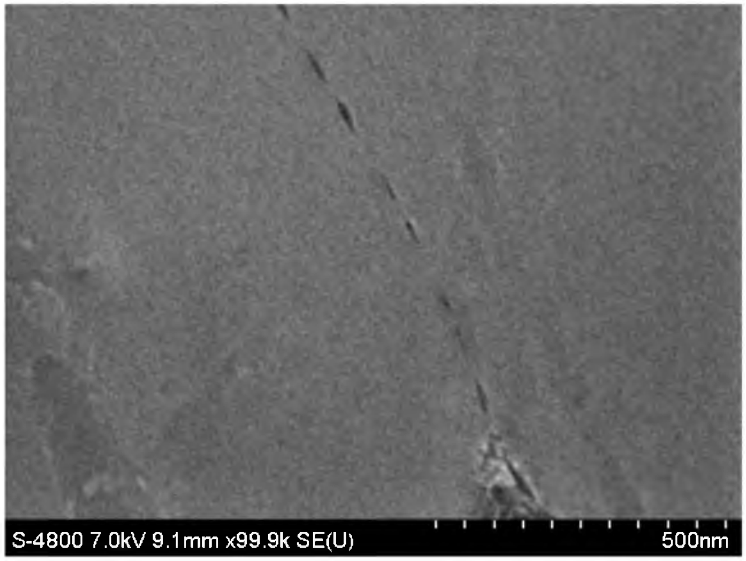

Figure 30 – SEM of sensitized aluminum 5083 sample

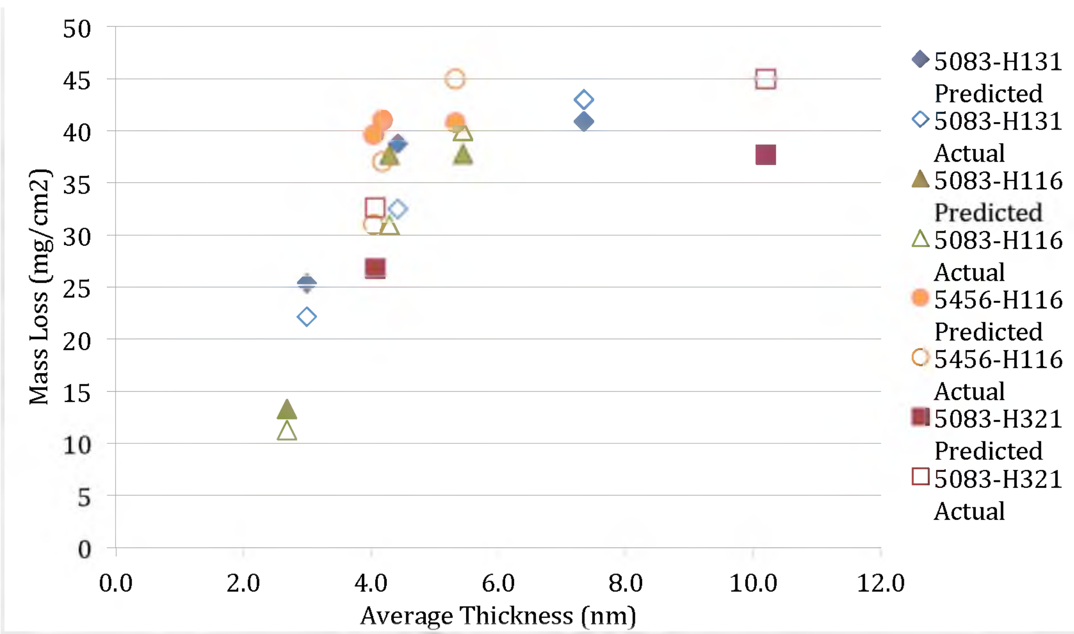

Figure 31 - 3-rate model comparison

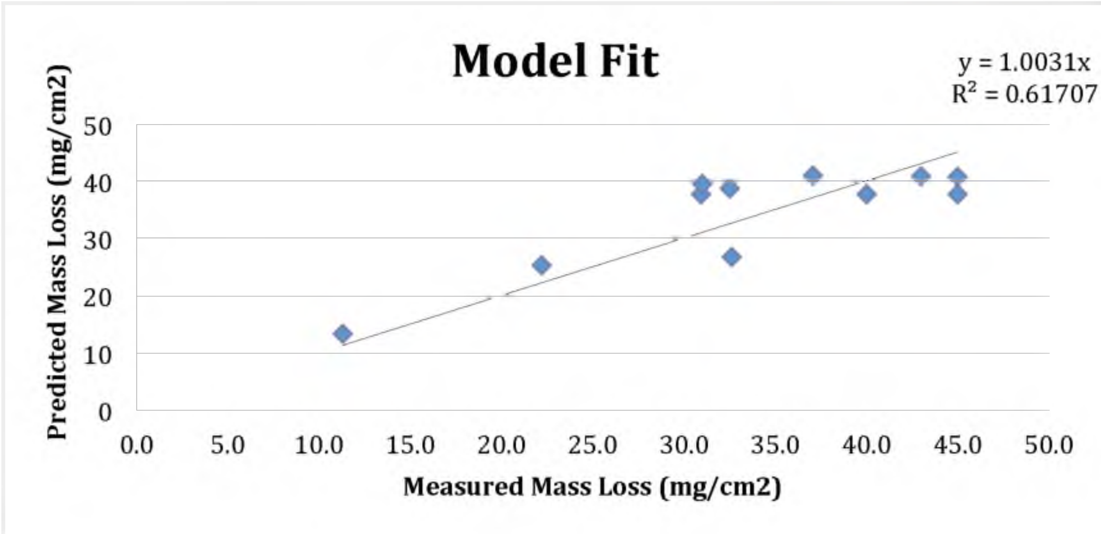

Figure 32 – 3-rate model fit

phase. This additional model, used in conjunction with the mass loss model presented here, allows for the accurate predict of mass loss and correspondingly of the service life of various 5000 series alloys.

6 SENSITIZATION PREDICTION APPLICATION

6.1 Sensitization Application Development

The developed models are valuable in the prediction of sensitization of an unknown sample only if they can be put into practical use. Analysis of the above model shows a fairly basic algebraic form, which can easily be applied in an elementary spreadsheet program. However, the other portion of the model reveals somewhat more complication, including infinite series, which typically uses a more rigorous mathematical application to find an accurate solution. However, given the challenging nature of the user interface of many of these mathematical applications, a simpler approach was taken. Initially, Visual Basic code was chosen as the simplest approach to present the developed models. Utilizing a simple user interface, the application lends itself to frequent and unhindered use, while still maintaining the mathematical integrity and sophistication of the models developed. The application was developed in a series of stages, working from the most simplified predictions, requiring little user input, to the most complex, where all the variables required in the developed models can be adjusted, to more accurately reflect the reality of the variability that can exist from sample to sample. Figure 33

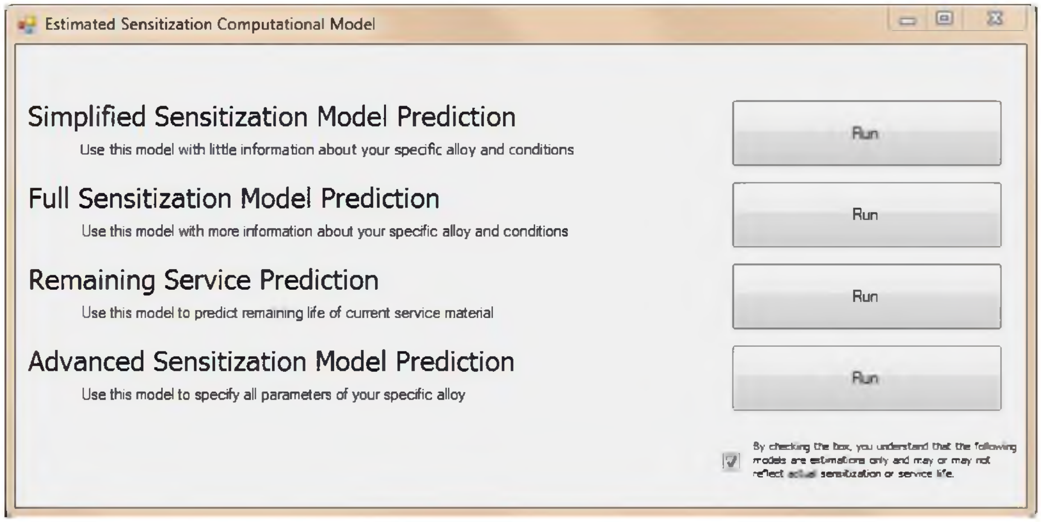

Figure 33 – Overall application screenshot

shows the opening screen of the application, which allows selection of the various levels of intricacy. Figure 34 to Figure 37 show the various prediction models within the application, allowing for flexibility by the user, based on the level of accuracy required and amount of sample data available. The preliminary code for this Visual Basic application can be found in Appendix A. It should be noted that although the code functions for basic analysis, rigorous testing was not completed.

This Visual Basic approach was used based on a preliminary model derivation for the β phase growth. After further review, a final model was developed for the β phase growth. Due to the nature of the revised model, it became apparent that a simpler approach could be applied, while maintaining the mathematical rigor of the β phase growth model.

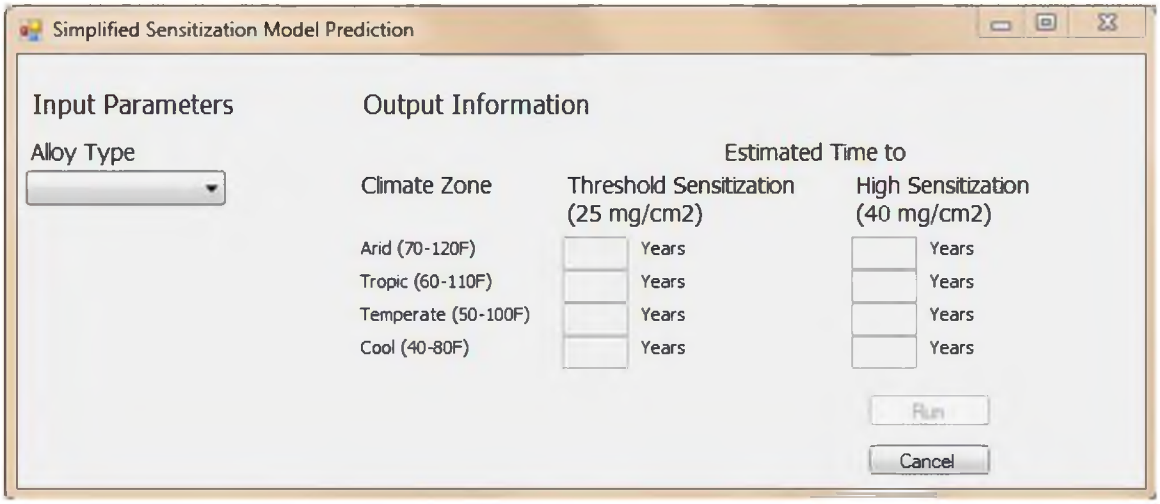

Figure 34 – Simplified model screenshot

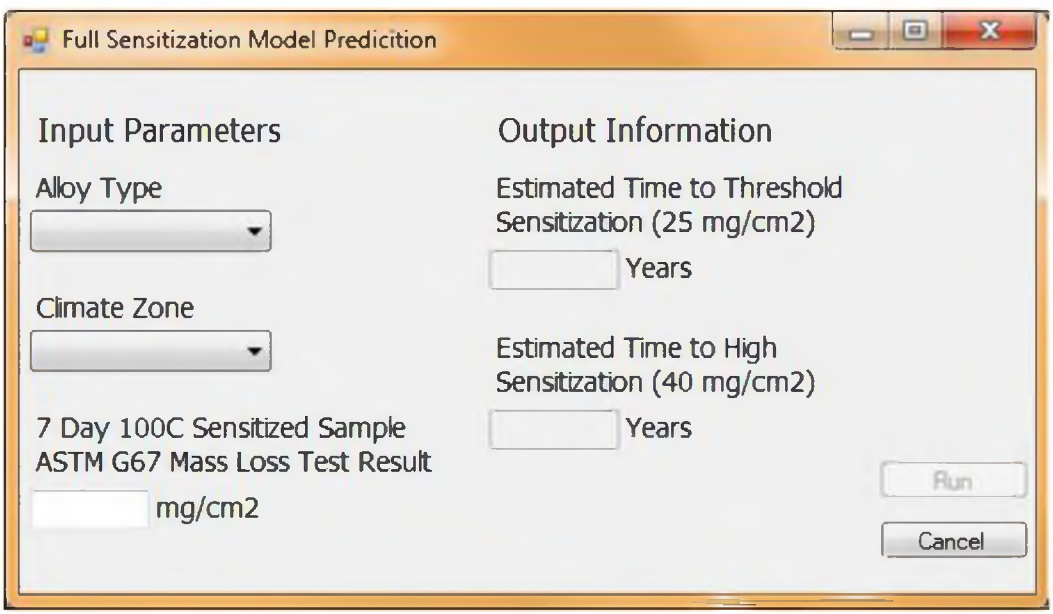

Figure 35 – Full model screenshot

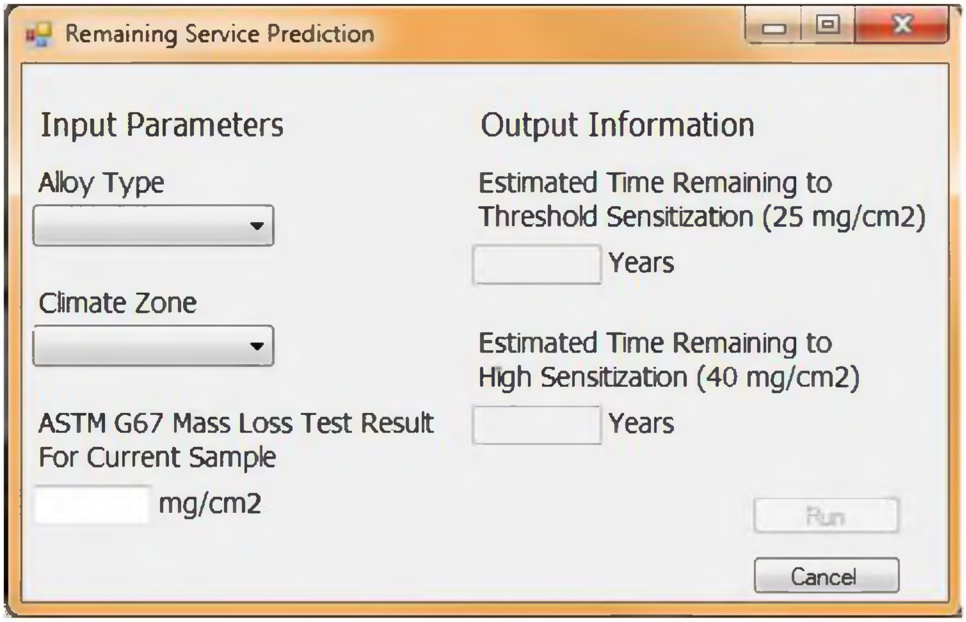

Figure 36 – Remaining service model screenshot

It still revolved around Visual Basic as the code, but was implemented into a spreadsheet as the shell medium, rather than an actual Visual Basic application. A similar setup was used, allowing for user flexibility in the amount of detailed information to be inputted. In addition, this new format allowed for additional output information to be readily available, including a comparison graph of the actual conditions specified with variations in two of the important parameters to visualize their effect on the mass loss or lifetime of the sample. Figure 38 and Figure 39 show screenshots of the new prediction model application.

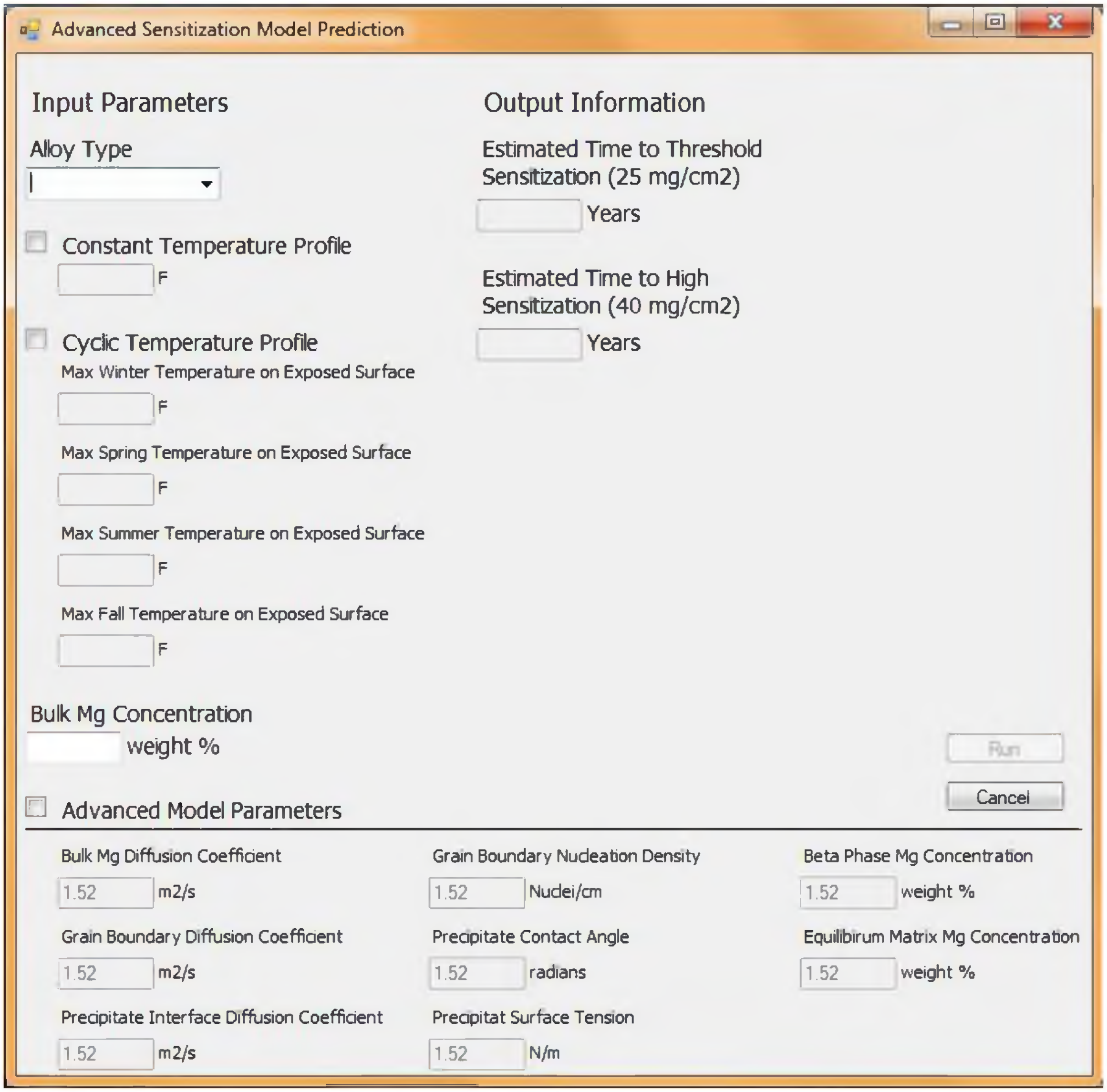

Figure 37 – Advanced model screenshot

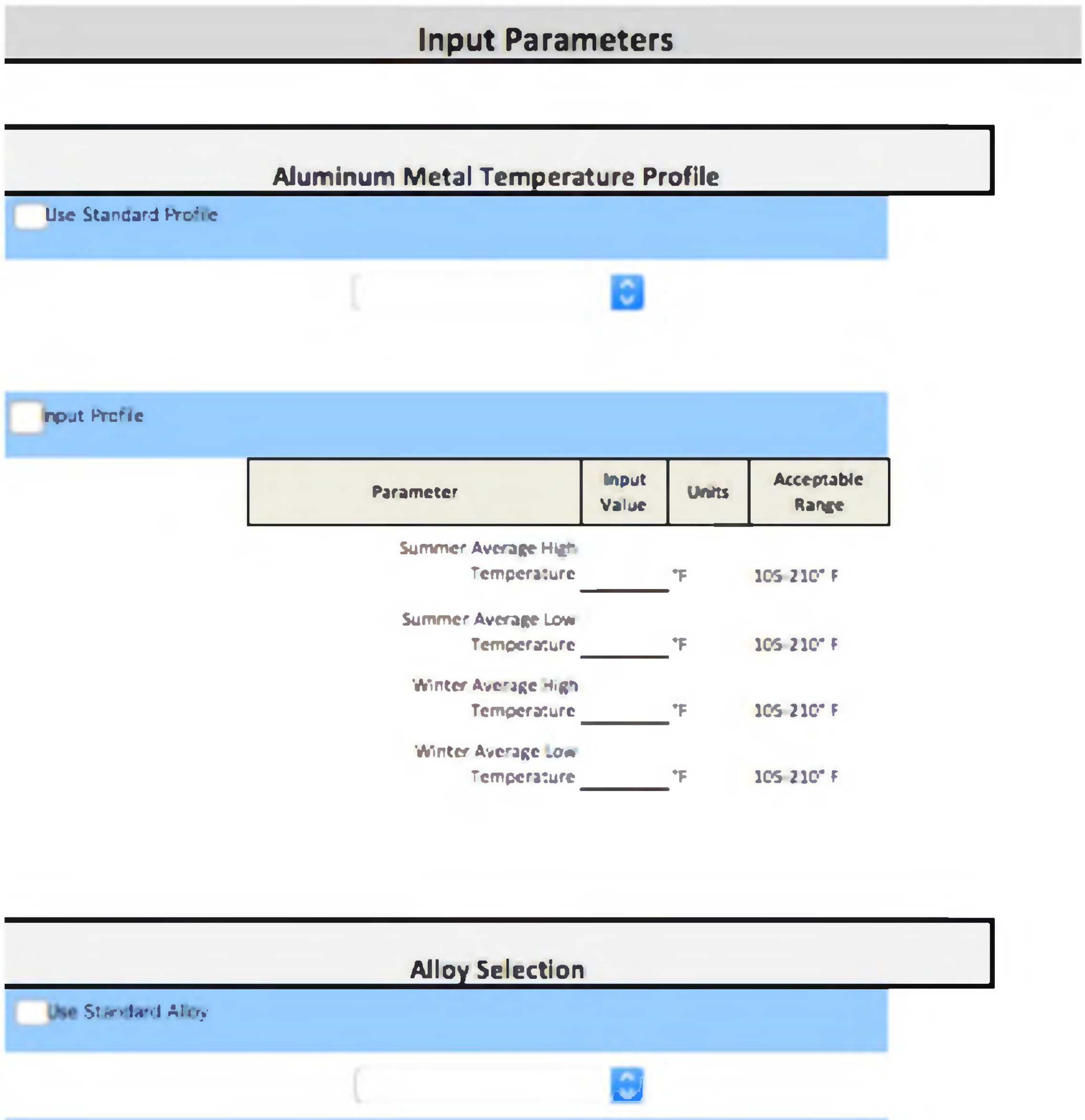

Figure 38 - Spreadsheet model input screenshot

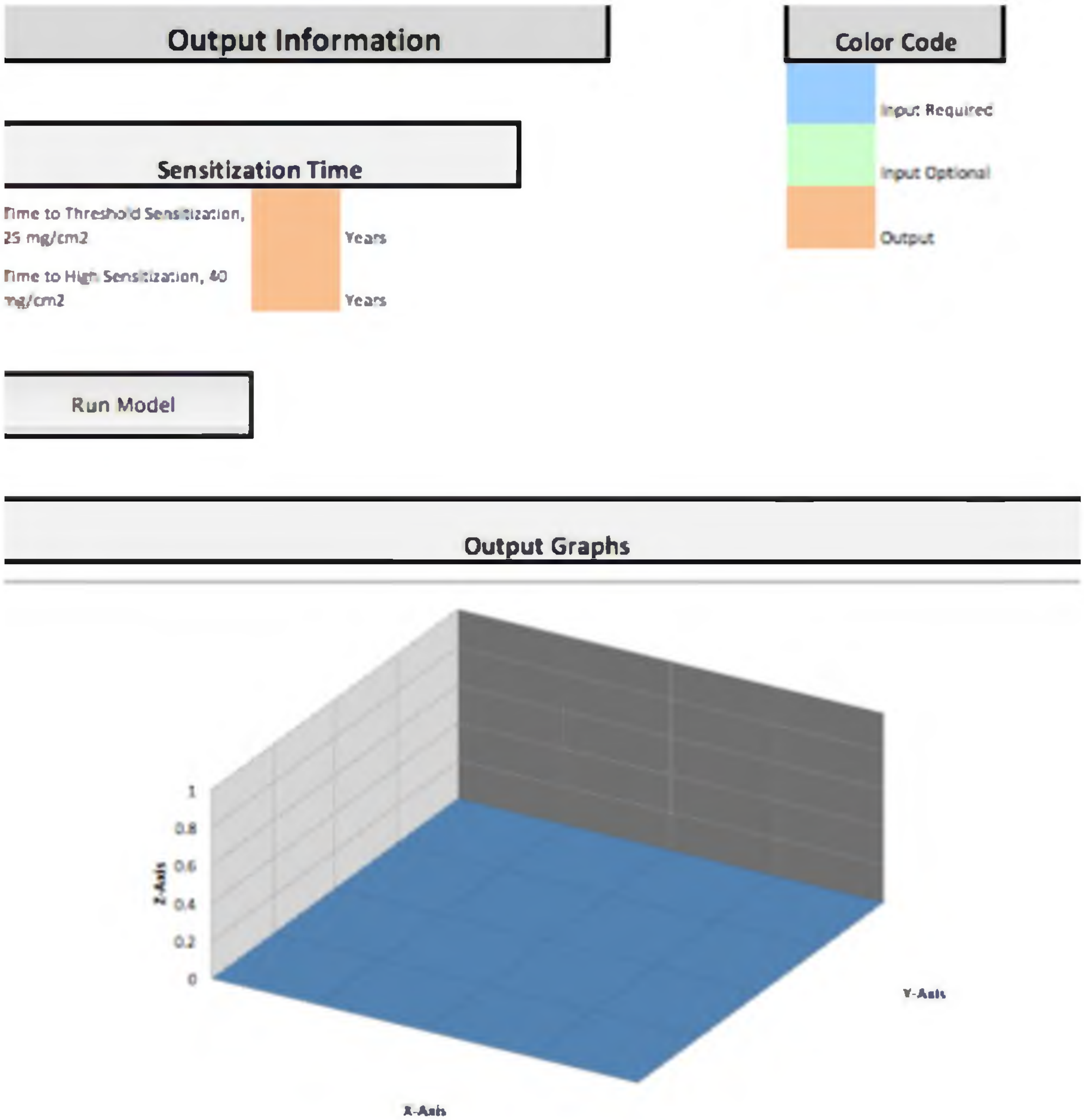

Figure 39 – Spreadsheet model output screenshot

6.2 Sensitization Prediction Details

In addition to the mass loss prediction model, the β phase growth model forms an intricate part of the sensitization prediction application code. In order to facilitate more widespread understanding and use of the model, a short User Guide was prepared, outlining the fundamental mathematical considerations of the two models as well as detailing the specifics of the Visual Basic coding behind the application operations.

6.2.1 Simplified Mathematical Fundamentals

At the most fundamental level, the mathematical model is derived from Fick's second law of diffusion, shown in Equation 52:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \qquad \text{Equation 52}$$

where C is the magnesium concentration, D is the diffusivity, x is the distance, and t is the time allowed for diffusion. In solving this equation for the system of interest, the grain boundary area of the aluminum alloy, the collector plate mechanism was chosen. The collector plate model defines the area of precipitation as a plate, to which the magnesium in the bulk aluminum diffuses. In essence, the plate collects the magnesium as it precipitates out along the grain boundary, growing the precipitate in this region. Because of the nature of precipitate growth along the grain boundary, this collector plate area must be allowed to vary as time progresses, especially in the case of long-term exposure, which is of significant importance for real world predictions. [59]

In addition to the diffusion component of the model, there are also two important steps in precipitate formation that are considered in the mathematics, including precipitate nucleation, as well as precipitate growth and coarsening. Initially, the majority of the grain boundaries within the material do not contain any precipitated β phase particles. As such, in order for these to form, nucleation of the precipitates must occur. Nucleation is the process by which a "seed" of the precipitate forms where one did not exist previously. This is a thermodynamic effect that is governed by classical nucleation theory, shown in Equation 53: [59]

$$\Delta g = -\frac{kT}{v_{at}{}^{P}} ln\left(\frac{C_{R_x}}{C_{eq}}\right) \qquad \text{Equation 53}$$

where Δg is the thermodynamic driving force, k is Boltzmann's constant, T is the temperature, $v_{at}{}^{P}$ is the atomic volume, C_{eq} is the equilibrium solute concentration and C_{R_x} is the average magnesium concentration at precipitate-free grain boundary area. Equation 53 clearly shows the dependence of this driving force on the temperature of the alloy, with increasing temperature leading to an increase in the nucleation or creation of β phase precipitates. In addition, it shows that nucleation is more likely to occur as the average concentration of magnesium at the grain boundary increase. [59]

Once a precipitate seed is formed or nucleated, this precipitate has a chance to grow or coarsen due to the additional diffusion of magnesium to the grain boundary near the nucleation site. For the model, a combination of two growth and coarsening mechanisms were applied, the Kirchner [54] and LSW [55], [56] methods. Both of these mechanisms were used to define the change in the volume of the precipitate as time progresses, with a transition from Kirchner to LSW as the volume fraction increases. As a result, a combination-coarsening model was developed and applied for the model. [59]

With these mathematical basics, the model execution utilizes the combined solutions of these various aspects to predict the β phase growth and distribution. This execution involves the use of finite differences to determine the β phase growth. The current status of the material is calculated at each point in time, utilizing a small time differential to move the alloy forward in time at the temperature of interest. This allows for simplified mathematical construction, while also providing sufficient mathematical accuracy to the complex solutions of these fundamental equations. Further information on the mathematical derivations and full details of the mathematical particulars can be found in [52] and [53]. [59]

6.2.2 Detailed Coding Structure

The Visual Basic code can be simplified into two basic units, consisting of user input and selection operations and the main model prediction functionality. Within the user input and selection operations, there are many modules, each specifically related to a particular section of the main spreadsheet. The main model prediction functionality is contained in a single larger module. Within both of these units, there are code comments that break up the coding further for ease of understanding. This allows another user to easily determine what functionality is contained in each part of the code and allows for future adjustment and enhancement as is required. In addition, each variable definition within the main model is clearly defined as to its function when it is defined. A detailed description of these two units follows below.

For the user input and selection operations, each module follows a similar structure. An example of the code for one of the modules is shown in Figure 40.

The module begins with a name callout of the input or selection operation, followed by a comment that outlines the main function of the module. For each module, the worksheets within the spreadsheet that are affect must be unprotected to allow alteration during the code execution. This step is then reversed at the end of the module to retain the integrity of the spreadsheets. In addition, each module resets the output results. Following these common basic steps, each module is broken up into two main sections, the first of which defines the actions to be taken if the input or selection is positive or true, meaning the user has selected that this functionality is desired. In the example above which checks for the utilization of a standard temperature profile, the first main section details the course of action if the user desires to utilize these predefined profiles, where as the second main section details the functions that follow if the user deselects this option.

Within each main section, the coding follows a typical pattern. First, the applicable objects within the spreadsheet are set to the appropriate state and value. For the above example under the first main section, the two objects of interest are the checkbox for selecting a variable user input temperature and the drop down menu box for selection of a specific temperature profile. Since this main section defines the states assuming the user desires to select a predefined temperature

```
Sub StandardTempCheck_Change()
  ' This Sub checks for a standard temperature input
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  If Sheets("Model").Shapes("StandardTempCheck").ControlFormat.Value =
1 Then
    Sheets("Model").Shapes("InputTempCheck").ControlFormat.Value = -
4146
    Sheets("Model").Shapes("StandardTempBox").ControlFormat.Enabled =
True
    Cells(7, 1).Interior.ColorIndex = 2
    Cells(4, 1).Interior.ColorIndex = 2
    Cells(5, 3).Interior.ColorIndex = 37
    Sheets("Model").Range("D9:D12").Interior.ColorIndex = 2
    Sheets("Model").Range("D9:D12").ClearContents
    Sheets("Model").Range("D9:D12").Locked = True
  ElseIf
Sheets("Model").Shapes("StandardTempCheck").ControlFormat.Value
= -4146 Then
    Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value = 0
    Sheets("Model").Shapes("StandardTempBox").ControlFormat.Enabled =
False
    Cells(4, 1).Interior.ColorIndex = 37
    Cells(7, 1).Interior.ColorIndex = 37
    Cells(5, 3).Interior.ColorIndex = 2
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub
```

Figure 40 – Example user input and selection operation module code

profile, the state of the user-input temperature checkbox is set to unchecked and the drop down box state is defined as functional for user selection.

The next portion of the code defines the color scheme that is adopted as a result of the user input. Returning to the above example, the cells containing the user-input checkbox and the select profile checkbox are reverting to a passive white color, signifying the user has selected between these two options. In addition, the cell containing the drop down menu of predefined temperature profiles has been highlighted in blue, signifying the need for additional user input or selection. Finally, the cells related to a user-input temperature profile are cleared, their color set to passive white and they are locked eliminating the user ability to utilize these cells. This same pattern is repeated in the second main section of the above example as well as for each individual module in all user input or selection operation modules contained in the model coding. For the complete coding of the user interface and selection operations, please see the Appendix.

The second basic unit of the visual basic code, the main model prediction functionality, is much more involved and broken up into three main sections, consisting of variable callout and definition, model mathematics for multiple data points, and model mathematics for a single data point.

Both of the model mathematics sections follow the same basic coding structure, with one main difference; the section for multiple data points runs through the coding several times producing additional data that can be viewed on the corresponding graph, whereas the section for a single data point only runs through the coding once. As such, only the coding for the section for a single data point will be reviewed and this understanding can be applied to the section for multiple data points with ease. The model mathematics is broken up into seven main parts. In the first part, the variables are assigned values for the model, based on the user input from the spreadsheet and standard values that remain unchanged between alloys. In parts II through V, the initial nucleation and volume of the precipitate are defined for the start of the model. The coding for this section can be seen in Figure 41.

The main part of the mathematics takes place in part VI, where the diffusion, nucleation, and growth of the β phase are calculated in small time step intervals. Within this part of the mathematics, the new coarsening model developed for this application is employed at each interval of time. The coding for this part can be seen in Figure 42.

The seventh and final part of the model mathematics involves the final output of the model, including the predicted service time of the alloy in question. This part also produces the data required for the graph selections given by the user. These seven parts are repeated again for each of the points required by the graph, based on the user selection prior to running the model prediction algorithm. As previously mentioned, these same parts also make up the third section of the overall model mathematics. There are portions of the coding removed, however, as only a single data point is generated in the third section. Only the key sections of the code have been shown here. For the complete code, please see the Appendix.

```
' Part II - Solute flow to the grain boundary
' Short term
If time < 200000000# Then
   Jms = (Ca - Cab) * (Dm ^ 0.5) / ((Pi * time) ^ 0.5)
   J = Jms
' Long term
Else
   ni = 0
   ani = 0
   Sumni = 0
   Do While (ni < 20)
      ani = Exp(-(((2 * ni + 1) * Pi / h) ^ 2) * Dm * time)
      Sumni = Sumni + ani
      ni = ni + 1
   Loop
   Jml = 4 * (Ca - Cab) * Dm / h * Sumni
   J = Jml
End If

' Part III - Initial volume of the precipitate
Js = ((A - Pi * R * R) / (2 * Pi * R * Delta / 2)) * J
Rsu = (1 / 3 * (1 + (4 + 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R /
Sin(Theta)) ^ 0.5)) ^ 0.5
If Rsu < 1.00000000000001 Then
   Rsu = 1.00000000000001

End If
Cosga = Cos(Theta) / Rsu
V0 = Tan(Theta) * (1 - 1 / (1 + Cosga) ^ 2)

' Part IV - Heterogeneous nucleaton rate at grain boundary
   ' Geometry of the precipitate
fPV = Pi * Tan(Theta) / 3 * (1 - 1 / (1 + Cosga) ^ 2)
Aa = 1 / (1 - Cosga * Cosga) ^ 0.5
Bb = Tan(Theta) * (Cosga) / (1 - Cosga * Cosga)
Cc = Bb * (1 - Cosga)
Dd = Cosga * Cosga / (1 - Cosga * Cosga) * Tan(Theta)
e = (1 - (Tan(Theta) * Tan(Theta) * Cosga * Cosga / (1 - Cosga * Cosga))) ^ 0.5
fPA = Pi / Bb / Bb / e * (Bb * Bb * (e * Aa * Aa + Bb * Bb * Log((1 + e) * Aa * Bb * R *
R)) - Aa * Dd * e * ((Aa * Dd * e) ^ 2 + Bb ^ 4) ^ 0.5 - (Bb ^ 4) * Log(Aa * Dd * e * R * R
+ (Bb ^ 4 * (R ^ 4) + (Aa * Dd * e * R * R) ^ 2) ^ 0.5))

' Part V - Concentration along the grain boundary
```

Figure 41 – Model mathematics parts II through V

```
   Ri = R
   Kc = 2 * fPA / 3 / fPV / R
   CRi = Cab * Exp(Gamma * vat / k / T * Kc)
   CRx = CRi + J / Delta / Db * (Ri * Ri / 2 - Rc * Rc * Log(Ri)) + J / Delta / Db / (Rc -
Ri) * (Rc * Rc * Rc * (Log(Rc) - 7 / 6) - Ri * (Rc * Rc * Log(Ri) - Rc * Rc - Ri * Ri / 6))
   Deltag = -k * T / vat * Log(CRx / Cab)
   Rs = -2 / 3 * fPA / fPV * Gamma / Deltag
   DeltaGs = 4 / 27 * fPA * fPA * fPA / fPV / fPV * Gamma * Gamma * Gamma / Deltag
/ Deltag
   Zed = vat / 2 / Pi / (Rs * Rs) * (Gamma / k / T) ^ 0.5
   Betas = 4 * Pi * Rs * Rs * Db * CRx / (a0) ^ 4
   Tao0 = 4 / 2 / Pi / Betas / Zed / Zed
   Rdta = 1 / (1 - Cosga * Cosga) - (Cosga * Cosga / (1 - Cosga ^ 2) + (Delta ^ 2) / 4 /
(R * R) * (1 - Cosga ^ 2) / (Cosga * Cosga) / (Tan(Theta)) ^ 2 + Delta / R /
Tan(Theta))

   If (Cc * R < (Delta / 2)) Then
      Vp = fPV * (R ^ 3)
   Else
      Vp = Pi * ((R + R * Rdta ^ 0.5) / 2) ^ 2 * Delta / 2
   End If
   Vavl = Delta / 2 - N * Vp
   favl = 2 * Vavl / Delta
   dNn = Delta * Delta / h * favl * N0 * Zed * Betas * Exp(-DeltaGs * 1 / k / T) * Exp(-
         Tao0 / time)
   time = time + dt
```

Figure 41 continued

```
' Part VI - Precipitate Growth over time,
  Do While (i < 100000000#)
    T = TempA * Sin(Pi / 43200 * time) + Temp0 '
    ' Short term
    If time < 200000000# Then
      Jms = (Ca - Cab) * (Dm ^ 0.5) / ((Pi * time) ^ 0.5)
      J = Jms
    ' Long term
    Else
      ni = 0
      ani = 0
      Sumni = 0
      Do While (ni < 20)

        ani = Exp(-(((2 * ni + 1) * Pi / h) ^ 2) * Dm * time)
        Sumni = Sumni + ani
        ni = ni + 1
      Loop
      Jml = 4 * (Ca - Cab) * Dm / h * Sumni
      J = Jml
    End If

    fPV = Pi * Tan(Theta) / 3 * (1 - 1 / (1 + Cosga) ^ 2)
    Aa = 1 / (1 - Cosga * Cosga) ^ 0.5
    Bb = Tan(Theta) * (Cosga) / (1 - Cosga * Cosga)
    Cc = Bb * (1 - Cosga)
    Dd = Cosga * Cosga / (1 - Cosga * Cosga) * Tan(Theta)
    e = (1 - (Tan(Theta) * Tan(Theta) * Cosga * Cosga / (1 - Cosga * Cosga))) ^ 0.5
    fPA = Pi / Bb / Bb / e * (Bb * Bb * (e * Aa * Aa + Bb * Bb * Log((1 + e) * Aa * Bb *
R * R)) - Aa * Dd * e * ((Aa * Dd * e) ^ 2 + Bb ^ 4) ^ 0.5 - Bb ^ 4 * Log(Aa * Dd *
      e * R * R + (Bb          ^ 4 * R ^ 4 + (Aa * Dd * e * R * R) ^ 2) ^ 0.5))
    Deltag = -k * T / vat * Log(CRx / Cab)
    Rs = -2 / 3 * fPA / fPV * Gamma / Deltag
    DeltaGs = 4 / 27 * fPA * fPA * fPA / fPV / fPV * Gamma * Gamma * Gamma /
Deltag / Deltag
    Zed = vat / 2 / Pi / (Rs * Rs) * (Gamma / k / T) ^ 0.5
    Betas = 4 * Pi * Rs * Rs * Db * CRx / (a0) ^ 4
    Tao0 = 4 / 2 / Pi / Betas / Zed / Zed
    Rdta = 1 / (1 - Cosga * Cosga) - (Cosga * Cosga / (1 - Cosga ^ 2) + (Delta ^ 2) / 4
/ (R * R) * (1 - Cosga ^ 2) / (Cosga * Cosga) / (Tan(Theta)) ^ 2 + Delta / R /
Tan(Theta))

    If (Cc * R < (Delta / 2)) Then
```

Figure 42 - Model mathematics part VI

```
    Vp = fPV * R ^ 3
  Else
    Vp = Pi * (((R + R * Rdta ^ 0.5) / 2) ^ 2) * Delta / 2
  End If

  Vavl = Delta / 2 - N * Vp
  favl = 2 * Vavl / Delta
  dNn = Delta * Delta / h * favl * N0 * Zed * Betas * Exp(-DeltaGs * 1 / k / T) *
Exp(-Tao0 /   time)
  Js = (((A - Pi * R * R) / (2 * Pi * R * Delta / 2)) * J - dNn * N * (A - Pi * R * R) / (1 -
N * Pi * R * R) * fPV * Rs ^ 3 / N / (Pi * R * Delta) * (Cb - Cab))
  If 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R / Sin(Theta) < -4 Then
   Js = -4 / (3 * 8.314 * T / Ds / Cs / Gamma / Omega * R * R / Sin(Theta)) + 1e-14

  End If
Rsu = (1 / 3 * (1 + (4 + 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R /
     Sin(Theta)) ^ 0.5)) ^ 0.5
  If Rsu < 1.00000000000001 Then
    Rsu = 1.00000000000001
  End If
  Cosga = Cos(Theta) / Rsu
  V1 = Tan(Theta) * (1 - 1 / (1 + Cosga) ^ 2)
  Ri = R
  Kc = 2 * fPA / 3 / fPV / R
  CRi = Cab * Exp(Gamma * vat / k / T * Kc)
  CRx = CRi + J / Delta / Db * (Ri * Ri / 2 - Rc * Rc * Log(Ri)) + J / Delta / Db / (Rc -
Ri) * (Rc * Rc * Rc * (Log(Rc) - 7 / 6) - Ri * (Rc * Rc * Log(Ri) - Rc * Rc - Ri * Ri / 6))

  ' Precipitate growth rate
  dVg = J * A / (Cb - Cab) - dNn * (Yita * fPV * Rs ^ 3) / N

  ' Coarsening rate
  Alpha = (2 * fPA * Gamma / 3 / fPV / k / T) * vat * Cab
  dVc = 4 / 9 * fPA * Alpha * Db / (Cb - Cab)

  ' Coarsening fraction
  fcoa = dVc / (dVg + dVc)

  ' Final growth rate
  dVf = fcoa * dVc + (1 - fcoa) * dVg

  ' Precipitate number change during the coarsening
```

Figure 42 continued

```
dNc = J / (fPV * R ^ 3) / (Cb - Cab) - N / (fPV * R ^ 3) * dVc

    ' Radius change rate
    dVm = (V1 - V0) / dt
    dRf = 1 / (Pi * V1 * R * R) * dVf - R / 3 / V1 * dVm

    ' Total number change rate
    If (-dNc) > dNn Then
      dN = fcoa * dNc
    Else
      dN = dNn
    End If

    R1 = R + dRf * dt
    N = N + dN * dt

    A1 = A + 4 * Pi * Db * dt
    A2 = 1 / N

    If A1 > A2 Then
      A = A2
    Else
      A = A1
    End If

    Rc = (A / Pi) ^ 0.5
    time = time + dt
    If R1 > 0 Then
      R = R1
    End If
    V0 = V1
    i = i + 1
    BetaTheta = R / ((A2 / Pi) ^ 0.5)
    ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
```

Figure 42 continued

6.3 Sensitization Application Validation

The effectiveness of the developed application is only as useful as the data it produces. As such, the application must be tested against a real world example. In particular, both sections of the mathematical model should be validated, as well as the corresponding output of sensitization, predicted by the above application.

As can be seen in Figure 43, there is good correlation between the application output results and the measured mass loss results particularly for the three different tempers of the 5083 alloy studied. There is less accurate correlation for the 5456 alloy studied.

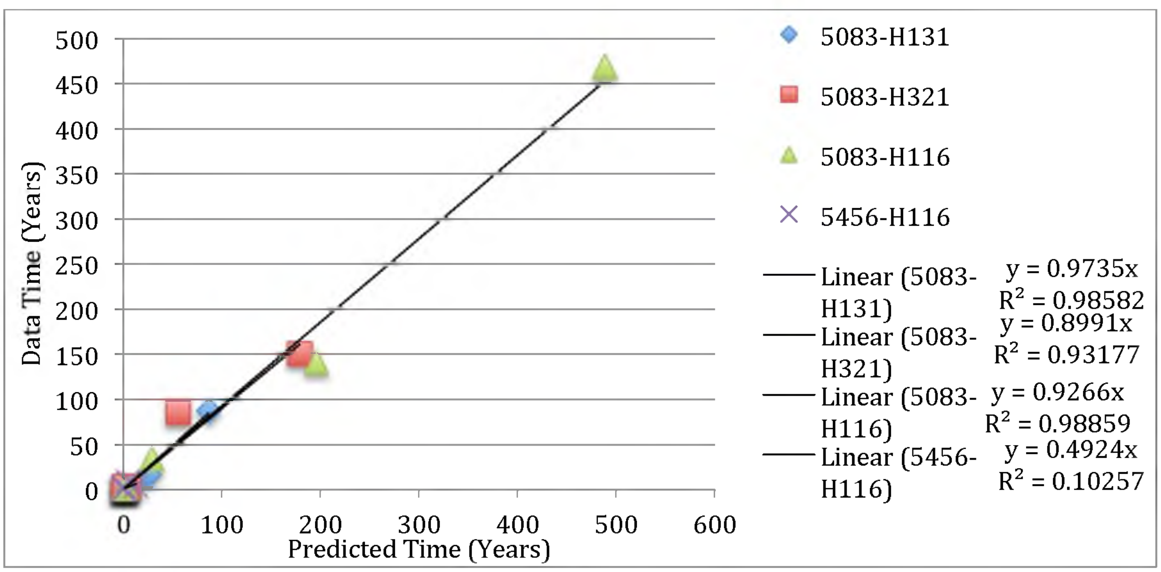

Figure 43 – Application versus test results

7 CONCLUSIONS

In the present work, the ASTM G67 standard test was modeled in order to predict the results of this test, given quantitative information about the presence of β phase within a given sample of interest. Preliminary experimentation was conducted in order to provide a basic understanding of underlying scientific reasoning behind the mass loss which occurs in the standardize test, due to the presence of β phase precipitates. This understanding facilitated the modeling of the chemical reactions, which occur during the ASTM G67 mass loss test on an aluminum 5000 series alloy.

This modeling was validated through the use of SEM and AFM techniques. SEM was used to gather the quantitative data on which the model was based and tested against for validity. The basic form of the model utilizes three separate dissolution rates, one for the grain boundary, one for the pre/thin β phase, and a final rate for the dissolution of β phase precipitates along the grain boundary. The presence of multiple rates during dissolution was confirmed with two different acids through AFM imaging.

In addition, this modeling effort was combined with previous work [52], [53] which provides the required quantitative information about the presence of β phase in the alloy. With this combination, a complete predictive model was coded into a simple spreadsheet based application. The predictive model allows for quantitative predictions of service life and expected mass loss after a given exposure time for an alloy of interest. This predictive model was validated using actual mass loss results from four different samples studied.

Given the limited number to alloys studied, future work is required to ensure model validation for a wider variety of 5xxx aluminum alloys. The need for this work is also apparent given the reduced accuracy of the prediction for the 5456 alloy studied. Additional research will be undertaken to better understand the differences between 5xxx alloys, as well as the corresponding effect on β phase precipitation and mass loss. With this understanding, the modeling application can be modified to allow specific inputs, such as alloy type, temper designation, yield strength, etc., from which the alloy parameters within the model can be estimated, in order to produce the most accurate results possible for new alloys of interest.

APPENDIX

A.1 Preliminary β Visual Basic Code

```
Public Class OuterForm

    'Setup the Outer Form
    Friend WithEvents SLabel As System.Windows.Forms.Label 'Simplified Model
Label
    Friend WithEvents SText As System.Windows.Forms.Label 'Simplified Model
Description
    Friend WithEvents SButton As System.Windows.Forms.Button 'Simplified Model
Run Button
    Friend WithEvents FLabel As System.Windows.Forms.Label 'Full Model Label
    Friend WithEvents FText As System.Windows.Forms.Label 'Full Model
Description
    Friend WithEvents FButton As System.Windows.Forms.Button ' Full Model Run
Button
    Friend WithEvents RLabel As System.Windows.Forms.Label 'Remaining Service
Time Label
    Friend WithEvents RText As System.Windows.Forms.Label 'Remaining Service
Time Description
    Friend WithEvents RButton As System.Windows.Forms.Button 'Remaining Service
Time Run Button
    Friend WithEvents ALabel As System.Windows.Forms.Label 'Advanced Model
Label
    Friend WithEvents AText As System.Windows.Forms.Label 'Advanced Model
Description
    Friend WithEvents AButton As System.Windows.Forms.Button 'Advanced Model
Run Button
    Friend WithEvents ReleaseBoxLabel As System.Windows.Forms.Label
'Release/Waiver Box Label
    Friend WithEvents ReleaseBox As System.Windows.Forms.CheckBox
'Release/Waiver Box
   'Format the Outer Form
    <System.Diagnostics.DebuggerStepThrough()> Private Sub InitializeComponent()
```

```
Me.SLabel = New System.Windows.Forms.Label()
Me.SText = New System.Windows.Forms.Label()
Me.SButton = New System.Windows.Forms.Button()
Me.FLabel = New System.Windows.Forms.Label()
Me.FText = New System.Windows.Forms.Label()
Me.FButton = New System.Windows.Forms.Button()
Me.RLabel = New System.Windows.Forms.Label()
Me.RText = New System.Windows.Forms.Label()
Me.RButton = New System.Windows.Forms.Button()
Me.ALabel = New System.Windows.Forms.Label()
Me.AText = New System.Windows.Forms.Label()
Me.AButton = New System.Windows.Forms.Button()
Me.ReleaseBoxLabel = New System.Windows.Forms.Label()
Me.ReleaseBox = New System.Windows.Forms.CheckBox()
Me.SuspendLayout()

'Simplified Model Label
Me.SLabel.AutoSize = True
Me.SLabel.Font = New System.Drawing.Font("Tahoma", 15.0!)
Me.SLabel.Location = New System.Drawing.Point(5, 40)
Me.SLabel.Name = "SLabel"
Me.SLabel.Size = New System.Drawing.Size(369, 24)
Me.SLabel.TabIndex = 0
Me.SLabel.Text = "Simplified Sensitization Model Prediction"

'Simplified Model Description
Me.SText.AutoSize = True
Me.SText.Font = New System.Drawing.Font("Tahoma", 8.0!)
Me.SText.Location = New System.Drawing.Point(45, 70)
Me.SText.Name = "SText"
Me.SText.Size = New System.Drawing.Size(370, 13)
Me.SText.TabIndex = 1
Me.SText.Text = "Use this model with little information about your specific alloy
and conditions"

'Simplified Model Run Button
Me.SButton.Enabled = False
Me.SButton.Location = New System.Drawing.Point(526, 40)
Me.SButton.Name = "SButton"
Me.SButton.Size = New System.Drawing.Size(200, 50)
Me.SButton.TabIndex = 2
Me.SButton.Text = "Run"

'Full Model Label
```

```
    Me.FLabel.AutoSize = True
    Me.FLabel.Font = New System.Drawing.Font("Tahoma", 15.0!)
    Me.FLabel.Location = New System.Drawing.Point(5, 100)
    Me.FLabel.Name = "FLabel"
    Me.FLabel.Size = New System.Drawing.Size(313, 24)
    Me.FLabel.TabIndex = 3
    Me.FLabel.Text = "Full Sensitization Model Prediction"

    'Full Model Description
    Me.FText.AutoSize = True
    Me.FText.Location = New System.Drawing.Point(45, 130)
    Me.FText.Name = "FText"
    Me.FText.Size = New System.Drawing.Size(366, 13)
    Me.FText.TabIndex = 4
    Me.FText.Text = "Use this model with more information about your specific
alloy and conditions"

    'Full Model Run Button
    Me.FButton.Enabled = False
    Me.FButton.Location = New System.Drawing.Point(526, 100)
    Me.FButton.Name = "FButton"
    Me.FButton.Size = New System.Drawing.Size(200, 50)
    Me.FButton.TabIndex = 5
    Me.FButton.Text = "Run"

    'Remaining Service Time Label
    Me.RLabel.AutoSize = True
    Me.RLabel.Font = New System.Drawing.Font("Tahoma", 15.0!)
    Me.RLabel.Location = New System.Drawing.Point(5, 160)
    Me.RLabel.Name = "RLabel"
    Me.RLabel.Size = New System.Drawing.Size(268, 24)
    Me.RLabel.TabIndex = 6
    Me.RLabel.Text = "Remaining Service Prediction"

    'Remaining Service Time Description
    Me.RText.AutoSize = True
    Me.RText.Location = New System.Drawing.Point(45, 190)
    Me.RText.Name = "RText"
    Me.RText.Size = New System.Drawing.Size(311, 13)
    Me.RText.TabIndex = 7
    Me.RText.Text = "Use this model to predict remaining life of current service
material"

    'Remaining Service Time Run Button
    Me.RButton.Enabled = False
```

```
    Me.RButton.Location = New System.Drawing.Point(526, 160)
    Me.RButton.Name = "RButton"
    Me.RButton.Size = New System.Drawing.Size(200, 50)
    Me.RButton.TabIndex = 8
    Me.RButton.Text = "Run"

    'Advanced Model Label
    Me.ALabel.AutoSize = True
    Me.ALabel.Font = New System.Drawing.Font("Tahoma", 15.0!)
    Me.ALabel.Location = New System.Drawing.Point(5, 220)
    Me.ALabel.Name = "ALabel"
    Me.ALabel.Size = New System.Drawing.Size(368, 24)
    Me.ALabel.TabIndex = 9
    Me.ALabel.Text = "Advanced Sensitization Model Prediction"

    'Advanced Model Description
    Me.AText.AutoSize = True
    Me.AText.Location = New System.Drawing.Point(45, 250)
    Me.AText.Name = "AText"
    Me.AText.Size = New System.Drawing.Size(290, 13)
    Me.AText.TabIndex = 10
    Me.AText.Text = "Use this model to specify all parameters of your specific alloy"

    'Advanced Model Run Button
    Me.AButton.Enabled = False
    Me.AButton.Location = New System.Drawing.Point(526, 220)
    Me.AButton.Name = "AButton"
    Me.AButton.Size = New System.Drawing.Size(200, 50)
    Me.AButton.TabIndex = 11
    Me.AButton.Text = "Run"

    'Release Box Label
    Me.ReleaseBoxLabel.Font = New System.Drawing.Font("Tahoma", 6.0!)
    Me.ReleaseBoxLabel.Location = New System.Drawing.Point(540, 290)
    Me.ReleaseBoxLabel.Name = "ReleaseBoxLabel1"
    Me.ReleaseBoxLabel.Size = New System.Drawing.Size(200, 50)
    Me.ReleaseBoxLabel.TabIndex = 12
    Me.ReleaseBoxLabel.Text = "By checking the box, you understand that the
following models are estimations onl" & "y and may or may not reflect actual
sensitization or service life."

    'Release Box
    Me.ReleaseBox.AutoSize = True
    Me.ReleaseBox.Location = New System.Drawing.Point(520, 300)
    Me.ReleaseBox.Name = "ReleaseBox"
```

```
        Me.ReleaseBox.Size = New System.Drawing.Size(15, 14)
        Me.ReleaseBox.TabIndex = 13

        'Adds all relevant components to the OuterForm
        Me.AutoSize = True
        Me.ClientSize = New System.Drawing.Size(284, 262)
        Me.Controls.Add(Me.SLabel)
        Me.Controls.Add(Me.SText)
        Me.Controls.Add(Me.SButton)
        Me.Controls.Add(Me.FLabel)
        Me.Controls.Add(Me.FText)
        Me.Controls.Add(Me.FButton)
        Me.Controls.Add(Me.RLabel)
        Me.Controls.Add(Me.RText)
        Me.Controls.Add(Me.RButton)
        Me.Controls.Add(Me.ALabel)
        Me.Controls.Add(Me.AText)
        Me.Controls.Add(Me.AButton)
        Me.Controls.Add(Me.ReleaseBoxLabel)
        Me.Controls.Add(Me.ReleaseBox)
        Me.Name = "OuterForm"
        Me.Text = "Estimated Sensitization Computational Model"
        Me.ResumeLayout(False)
        Me.PerformLayout()

    End Sub

    'Ensure Release Box is Checked
    Private Sub ReleaseBox_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ReleaseBox.CheckedChanged

        'Enables/disables all model run buttons, based on Release/Waiver Box status
        If ReleaseBox.Checked = True Then
            SButton.Enabled = True
            FButton.Enabled = True
            RButton.Enabled = True
            AButton.Enabled = True
        ElseIf ReleaseBox.Checked = False Then
            SButton.Enabled = False
            FButton.Enabled = False
            RButton.Enabled = False
            AButton.Enabled = False
        End If

    End Sub
```

```
'Setup the Simplified Model Form
Friend WithEvents SForm As System.Windows.Forms.Form 'Simplified Model
Form
Friend WithEvents InputLabel As System.Windows.Forms.Label 'Input
Parameters Label
Friend WithEvents AlloyLabel As System.Windows.Forms.Label 'Input; Alloy Type
Label
Friend WithEvents SAlloyList As System.Windows.Forms.ComboBox 'Input; Alloy
List
Friend SAlloyListEnable As Boolean 'Check if Alloy Selection is complete
Friend WithEvents SRunButton As System.Windows.Forms.Button 'Simplified
Model Run Button
Friend WithEvents SXButton As System.Windows.Forms.Button 'Simplified Model
Cancel Button
Friend WithEvents OutputLabel As System.Windows.Forms.Label 'Output
Information Label
Friend WithEvents EstimatedTimeLabel As System.Windows.Forms.Label
'Output; Estimated Time Label
Friend WithEvents SensitizedTimeLabel As System.Windows.Forms.Label
'Output; Sensitization Time Label
Friend WithEvents FailureTimeLabel As System.Windows.Forms.Label 'Output;
High Sensitization Time Label
Friend WithEvents ClimateLabel As System.Windows.Forms.Label 'Output;
Climate Label
Friend WithEvents AridLabel As System.Windows.Forms.Label 'Output; Arid
Climate Label
Friend WithEvents TropicLabel As System.Windows.Forms.Label 'Output; Tropic
Climate Label
Friend WithEvents TemperateLabel As System.Windows.Forms.Label 'Output;
Temperate Climate Label
Friend WithEvents CoolLabel As System.Windows.Forms.Label 'Output; Cool
Climate Label
Friend WithEvents AridSenText As System.Windows.Forms.TextBox 'Output; Arid
Climate Sensitization Time Text
Friend WithEvents TropSenText As System.Windows.Forms.TextBox 'Output;
Tropic Climate Sensitization Time Text
Friend WithEvents TempSenText As System.Windows.Forms.TextBox 'Output;
Temperate Climate Sensitization Time Text
Friend WithEvents CoolSenText As System.Windows.Forms.TextBox 'Output; Cool
Climate Sensitization Time Text
Friend WithEvents AridFailText As System.Windows.Forms.TextBox 'Output; Arid
Climate High Sensitization Time Text
Friend WithEvents TropFailText As System.Windows.Forms.TextBox 'Output;
Tropic Climate High Sensitization Time Text
```

```
    Friend WithEvents TempFailText As System.Windows.Forms.TextBox 'Output; Temperate Climate High Sensitization Time Text
    Friend WithEvents CoolFailText As System.Windows.Forms.TextBox 'Output; Cool Climate High Sensitization Time Text
    Friend WithEvents ASUnitLabel As System.Windows.Forms.Label 'Output; Arid Climate Sensitization Time Unit Label
    Friend WithEvents TS1UnitLabel As System.Windows.Forms.Label 'Output; Tropic Climate Sensitization Time Unit Label
    Friend WithEvents TS2UnitLabel As System.Windows.Forms.Label 'Output; Temperate Climate Sensitization Time Unit Label
    Friend WithEvents CSUnitLabel As System.Windows.Forms.Label 'Output; Cool Climate Sensitization Time Unit Label
    Friend WithEvents AFUnitLabel As System.Windows.Forms.Label 'Output; Arid Climate High Sensitization Time Unit Label
    Friend WithEvents TF1UnitLabel As System.Windows.Forms.Label 'Output; Tropic Climate High Sensitization Time Unit Label
    Friend WithEvents TF2UnitLabel As System.Windows.Forms.Label 'Output; Temperate Climate High Sensitization Time Unit Label
    Friend WithEvents CFUnitLabel As System.Windows.Forms.Label 'Output; Cool Climate High Sensitization Time Unit Label

    Private Sub SModel(ByVal sender As Object, ByVal e As System.EventArgs) Handles SButton.Click

        ' Format the Simplified Form
        Me.SForm = New System.Windows.Forms.Form
        Me.InputLabel = New System.Windows.Forms.Label
        Me.AlloyLabel = New System.Windows.Forms.Label
        Me.SAlloyList = New System.Windows.Forms.ComboBox
        Me.SRunButton = New System.Windows.Forms.Button
        Me.SXButton = New System.Windows.Forms.Button
        Me.OutputLabel = New System.Windows.Forms.Label
        Me.EstimatedTimeLabel = New System.Windows.Forms.Label
        Me.SensitizedTimeLabel = New System.Windows.Forms.Label
        Me.FailureTimeLabel = New System.Windows.Forms.Label
        Me.ClimateLabel = New System.Windows.Forms.Label
        Me.AridLabel = New System.Windows.Forms.Label
        Me.TropicLabel = New System.Windows.Forms.Label
        Me.TemperateLabel = New System.Windows.Forms.Label
        Me.CoolLabel = New System.Windows.Forms.Label
        Me.AridSenText = New System.Windows.Forms.TextBox
        Me.TropSenText = New System.Windows.Forms.TextBox
        Me.TempSenText = New System.Windows.Forms.TextBox
        Me.CoolSenText = New System.Windows.Forms.TextBox
        Me.AridFailText = New System.Windows.Forms.TextBox
```

```
Me.TropFailText = New System.Windows.Forms.TextBox
Me.TempFailText = New System.Windows.Forms.TextBox
Me.CoolFailText = New System.Windows.Forms.TextBox
Me.ASUnitLabel = New System.Windows.Forms.Label
Me.TS1UnitLabel = New System.Windows.Forms.Label
Me.TS2UnitLabel = New System.Windows.Forms.Label
Me.CSUnitLabel = New System.Windows.Forms.Label
Me.AFUnitLabel = New System.Windows.Forms.Label
Me.TF1UnitLabel = New System.Windows.Forms.Label
Me.TF2UnitLabel = New System.Windows.Forms.Label
Me.CFUnitLabel = New System.Windows.Forms.Label

'Input Parameters Label
Me.InputLabel.Location = New System.Drawing.Point(5, 20)
Me.InputLabel.AutoSize = True
Me.InputLabel.Font = New Font("Tahoma", 12)
Me.InputLabel.Text = "Input Parameters"

'Input; Alloy Type Label
Me.AlloyLabel.Location = New System.Drawing.Point(5, 50)
Me.AlloyLabel.AutoSize = True
Me.AlloyLabel.Font = New Font("Tahoma", 10)
Me.AlloyLabel.Text = "Alloy Type"

'Input; Alloy List
Me.SAlloyList.Location = New System.Drawing.Point(5, 70)
Me.SAlloyList.DropDownStyle = ComboBoxStyle.DropDownList
Me.SAlloyList.Items.Add("5083-H131")
Me.SAlloyList.Items.Add("5083-H116")
Me.SAlloyList.Items.Add("5083-H321")
Me.SAlloyList.Items.Add("5456-H116")
Me.SAlloyListEnable = False

'Simplified Model Run Button
Me.SRunButton.Location = New System.Drawing.Point(515, 205)
Me.SRunButton.Size = New System.Drawing.Size(75, 20)
Me.SRunButton.Enabled = False
Me.SRunButton.Text = "Run"

'Simplified Model Cancel Button
Me.SXButton.Location = New System.Drawing.Point(515, 235)
Me.SXButton.Size = New System.Drawing.Size(75, 20)
Me.SXButton.Text = "Cancel"

'Output Information Label
```

```
Me.OutputLabel.Location = New System.Drawing.Point(205, 20)
Me.OutputLabel.AutoSize = True
Me.OutputLabel.Font = New Font("Tahoma", 12)
Me.OutputLabel.Text = "Output Information"

'Output; Estimated Time Label
Me.EstimatedTimeLabel.Location = New System.Drawing.Point(425, 50)
Me.EstimatedTimeLabel.Size = New System.Drawing.Point(250, 20)
Me.EstimatedTimeLabel.Font = New Font("Tahoma", 10)
Me.EstimatedTimeLabel.Text = "Estimated Time to"

'Output; Sensitization Time Label
Me.SensitizedTimeLabel.Location = New System.Drawing.Point(330, 70)
Me.SensitizedTimeLabel.Size = New System.Drawing.Point(175, 40)
Me.SensitizedTimeLabel.Font = New Font("Tahoma", 10)
Me.SensitizedTimeLabel.Text = "Threshold Sensitization     (25 mg/cm2)"

'Output; High Sensitization Time Label
Me.FailureTimeLabel.Location = New System.Drawing.Point(505, 70)
Me.FailureTimeLabel.Size = New System.Drawing.Point(175, 40)
Me.FailureTimeLabel.Font = New Font("Tahoma", 10)
Me.FailureTimeLabel.Text = "High Sensitization          (40 mg/cm2)"

'Output; Climate Label
Me.ClimateLabel.Location = New System.Drawing.Point(205, 70)
Me.ClimateLabel.Size = New System.Drawing.Point(125, 40)
Me.ClimateLabel.Font = New Font("Tahoma", 10)
Me.ClimateLabel.Text = "Climate Zone"

'Output; Arid Climate Label
Me.AridLabel.Location = New System.Drawing.Point(205, 110)
Me.AridLabel.Size = New System.Drawing.Point(125, 20)
Me.AridLabel.Font = New Font("Tahoma", 8)
Me.AridLabel.Text = "Arid (70-120F)"

'Output; Tropic Climate Label
Me.TropicLabel.Location = New System.Drawing.Point(205, 130)
Me.TropicLabel.Size = New System.Drawing.Point(125, 20)
Me.TropicLabel.Font = New Font("Tahoma", 8)
Me.TropicLabel.Text = "Tropic (60-110F)"

'Output; Temperate Climate Label
Me.TemperateLabel.Location = New System.Drawing.Point(205, 150)
Me.TemperateLabel.Size = New System.Drawing.Point(125, 20)
Me.TemperateLabel.Font = New Font("Tahoma", 8)
```

```
Me.TemperateLabel.Text = "Temperate (50-100F)"

'Output; Cool Climate Label
Me.CoolLabel.Location = New System.Drawing.Point(205, 170)
Me.CoolLabel.Size = New System.Drawing.Point(125, 20)
Me.CoolLabel.Font = New Font("Tahoma", 8)
Me.CoolLabel.Text = "Cool (40-80F)"

'Output; Arid Climate Sensitization Time Text
Me.AridSenText.Location = New System.Drawing.Point(330, 110)
Me.AridSenText.Size = New System.Drawing.Point(40, 20)
Me.AridSenText.Enabled = False
Me.AridSenText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Tropic Climate Sensitization Time Text
Me.TropSenText.Location = New System.Drawing.Point(330, 130)
Me.TropSenText.Size = New System.Drawing.Point(40, 20)
Me.TropSenText.Enabled = False
Me.TropSenText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Temperate Climate Sensitization Time Text
Me.TempSenText.Location = New System.Drawing.Point(330, 150)
Me.TempSenText.Size = New System.Drawing.Point(40, 20)
Me.TempSenText.Enabled = False
Me.TempSenText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Cool Climate Sensitization Time Text
Me.CoolSenText.Location = New System.Drawing.Point(330, 170)
Me.CoolSenText.Size = New System.Drawing.Point(40, 20)
Me.CoolSenText.Enabled = False
Me.CoolSenText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Arid Climate Sensitization Time Unit Label
Me.ASUnitLabel.Location = New System.Drawing.Point(375, 110)
Me.ASUnitLabel.Size = New System.Drawing.Point(80, 20)
Me.ASUnitLabel.Font = New Font("Tahoma", 8)
Me.ASUnitLabel.Text = "Years"

'Output; Tropic Climate Sensitization Time Unit Label
Me.TS1UnitLabel.Location = New System.Drawing.Point(375, 130)
Me.TS1UnitLabel.Size = New System.Drawing.Point(80, 20)
Me.TS1UnitLabel.Font = New Font("Tahoma", 8)
Me.TS1UnitLabel.Text = "Years"

'Output; Temperate Climate Sensitization Time Unit Label
```

```
Me.TS2UnitLabel.Location = New System.Drawing.Point(375, 150)
Me.TS2UnitLabel.Size = New System.Drawing.Point(80, 20)
Me.TS2UnitLabel.Font = New Font("Tahoma", 8)
Me.TS2UnitLabel.Text = "Years"

'Output; Cool Climate Sensitization Time Unit Label
Me.CSUnitLabel.Location = New System.Drawing.Point(375, 170)
Me.CSUnitLabel.Size = New System.Drawing.Point(80, 20)
Me.CSUnitLabel.Font = New Font("Tahoma", 8)
Me.CSUnitLabel.Text = "Years"

'Output; Arid Climate High Sensitization Time Text
Me.AridFailText.Location = New System.Drawing.Point(505, 110)
Me.AridFailText.Size = New System.Drawing.Point(40, 20)
Me.AridFailText.Enabled = False
Me.AridFailText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Tropic Climate High Sensitization Time Text
Me.TropFailText.Location = New System.Drawing.Point(505, 130)
Me.TropFailText.Size = New System.Drawing.Point(40, 20)
Me.TropFailText.Enabled = False
Me.TropFailText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Temperate Climate High Sensitization Time Text
Me.TempFailText.Location = New System.Drawing.Point(505, 150)
Me.TempFailText.Size = New System.Drawing.Point(40, 20)
Me.TempFailText.Enabled = False
Me.TempFailText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Cool Climate High Sensitization Time Text
Me.CoolFailText.Location = New System.Drawing.Point(505, 170)
Me.CoolFailText.Size = New System.Drawing.Point(40, 20)
Me.CoolFailText.Enabled = False
Me.CoolFailText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Arid Climate High Sensitization Time Unit Label
Me.AFUnitLabel.Location = New System.Drawing.Point(550, 110)
Me.AFUnitLabel.Size = New System.Drawing.Point(80, 20)
Me.AFUnitLabel.Font = New Font("Tahoma", 8)
Me.AFUnitLabel.Text = "Years"

'Output; Tropic Climate High Sensitization Time Unit Label
Me.TF1UnitLabel.Location = New System.Drawing.Point(550, 130)
Me.TF1UnitLabel.Size = New System.Drawing.Point(80, 20)
Me.TF1UnitLabel.Font = New Font("Tahoma", 8)
```

```
Me.TF1UnitLabel.Text = "Years"

'Output; Temperate Climate High Sensitization Time Unit Label
Me.TF2UnitLabel.Location = New System.Drawing.Point(550, 150)
Me.TF2UnitLabel.Size = New System.Drawing.Point(80, 20)
Me.TF2UnitLabel.Font = New Font("Tahoma", 8)
Me.TF2UnitLabel.Text = "Years"

'Output; Cool Climate High Sensitization Time Unit Label
Me.CFUnitLabel.Location = New System.Drawing.Point(550, 170)
Me.CFUnitLabel.Size = New System.Drawing.Point(80, 20)
Me.CFUnitLabel.Font = New Font("Tahoma", 8)
Me.CFUnitLabel.Text = "Years"

'Adds all relevant components to the Simplified Model Form
SForm.AutoSize = True
SForm.Text = "Simplified Sensitization Model Prediction"
SForm.Controls.Add(Me.InputLabel)
SForm.Controls.Add(Me.AlloyLabel)
SForm.Controls.Add(Me.SAlloyList)
SForm.Controls.Add(Me.SRunButton)
SForm.Controls.Add(Me.SXButton)
SForm.Controls.Add(Me.OutputLabel)
SForm.Controls.Add(Me.EstimatedTimeLabel)
SForm.Controls.Add(Me.SensitizedTimeLabel)
SForm.Controls.Add(Me.FailureTimeLabel)
SForm.Controls.Add(Me.ClimateLabel)
SForm.Controls.Add(Me.AridLabel)
SForm.Controls.Add(Me.TropicLabel)
SForm.Controls.Add(Me.TemperateLabel)
SForm.Controls.Add(Me.CoolLabel)
SForm.Controls.Add(Me.AridSenText)
SForm.Controls.Add(Me.TropSenText)
SForm.Controls.Add(Me.TempSenText)
SForm.Controls.Add(Me.CoolSenText)
SForm.Controls.Add(Me.ASUnitLabel)
SForm.Controls.Add(Me.TS1UnitLabel)
SForm.Controls.Add(Me.TS2UnitLabel)
SForm.Controls.Add(Me.CSUnitLabel)
SForm.Controls.Add(Me.AridFailText)
SForm.Controls.Add(Me.TropFailText)
SForm.Controls.Add(Me.TempFailText)
SForm.Controls.Add(Me.CoolFailText)
SForm.Controls.Add(Me.AFUnitLabel)
SForm.Controls.Add(Me.TF1UnitLabel)
```

```
        SForm.Controls.Add(Me.TF2UnitLabel)
        SForm.Controls.Add(Me.CFUnitLabel)
        SForm.Show()

    End Sub

    'Ensure Simplified Model Alloy Selection
    Private Sub SAlloyList_Enable(ByVal sender As Object, ByVal e As
System.EventArgs)    Handles SAlloyList.SelectedIndexChanged

        AridSenText.Text = ""
        TropSenText.Text = ""
        TempSenText.Text = ""
        CoolSenText.Text = ""
        AridFailText.Text = ""
        TropFailText.Text = ""
        TempFailText.Text = ""
        CoolFailText.Text = ""

        If 0 <= SAlloyList.SelectedIndex <= 3 Then
            SAlloyListEnable = True
        End If

        If SAlloyListEnable = True Then
            SRunButton.Enabled = True
        End If

    End Sub

    'Simplified Model Run
    Private Sub SRunButton_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles SRunButton.Click

        If SAlloyList.SelectedIndex = 0 Then
            AridSenText.Text = 0.04
            TropSenText.Text = 0.47
            TempSenText.Text = 2.92
            CoolSenText.Text = 3365
            AridFailText.Text = 0.1
            TropFailText.Text = 1.01
            TempFailText.Text = 6.75
            CoolFailText.Text = "-"

        ElseIf SAlloyList.SelectedIndex = 1 Then
            AridSenText.Text = 0.04
```

```
            TropSenText.Text = 0.47
            TempSenText.Text = 2.92
            CoolSenText.Text = 3365
            AridFailText.Text = 0.1
            TropFailText.Text = 1.01
            TempFailText.Text = 6.75
            CoolFailText.Text = "-"

        ElseIf SAlloyList.SelectedIndex = 2 Then
            AridSenText.Text = 0.04
            TropSenText.Text = 0.47
            TempSenText.Text = 2.92
            CoolSenText.Text = 3365
            AridFailText.Text = 0.1
            TropFailText.Text = 1.01
            TempFailText.Text = 6.75
            CoolFailText.Text = "-"

        ElseIf SAlloyList.SelectedIndex = 3 Then
            AridSenText.Text = 0.04
            TropSenText.Text = 0.47
            TempSenText.Text = 2.92
            CoolSenText.Text = 3365
            AridFailText.Text = 0.1
            TropFailText.Text = 1.01
            TempFailText.Text = 6.75
            CoolFailText.Text = "-"

        End If


    End Sub

    'Simplified Model Cancel Button
    Private Sub SXButton_Click(ByVal sender As Object, ByVal e As System.EventArgs)
Handles SXButton.Click

        SForm.Close()

    End Sub

    'Setup the Full Model Form
    Friend WithEvents FForm As System.Windows.Forms.Form 'Full Model Form
    Friend WithEvents FAlloyList As System.Windows.Forms.ComboBox 'Input; Alloy
List
```

```
    Friend FAlloyListEnable As Boolean 'Check if Alloy Selection is complete
    Friend WithEvents TempLabel As System.Windows.Forms.Label 'Input; Temp
Label
    Friend WithEvents FTempList As System.Windows.Forms.ComboBox 'Input;
Temp List
    Friend FTempListEnable As Boolean 'Check if Temp Selection is complete
    Friend WithEvents SevenDayTestLabel As System.Windows.Forms.Label 'Input; 7
Day Mass Lost Test Result Label
    Friend WithEvents SevenDayTestText As System.Windows.Forms.TextBox 'Input;
7 Day Mass Lost Test Result Text
    Friend WithEvents SevenDayUnitLabel As System.Windows.Forms.Label 'Input; 7
Day Mass Lost Test Result Unit Label
    Friend SevenDayTestEnable As Boolean 'Check if 7 Day Mass Lost Test Result is
inputted
    Friend WithEvents FRunButton As System.Windows.Forms.Button 'Full Model
Run Button
    Friend WithEvents FXButton As System.Windows.Forms.Button 'Full Model
Cancel Button
    Friend WithEvents SensitizedTimeText As System.Windows.Forms.TextBox
'Output; Sensitization Time Text
    Friend WithEvents SenTimeUnitLabel As System.Windows.Forms.Label 'Output;
Sensitization Time Unit Label
    Friend WithEvents FailureTimeText As System.Windows.Forms.TextBox 'Output;
High Sensitization Time Text
    Friend WithEvents FailTimeUnitLabel As System.Windows.Forms.Label 'Output;
High Sensitization Time Unit Label

    Private Sub FModel(ByVal sender As System.Object, ByVal e As System.EventArgs)
Handles FButton.Click

        'Format the Full Model Form
        Me.FForm = New System.Windows.Forms.Form
        Me.InputLabel = New System.Windows.Forms.Label
        Me.AlloyLabel = New System.Windows.Forms.Label
        Me.FAlloyList = New System.Windows.Forms.ComboBox
        Me.TempLabel = New System.Windows.Forms.Label
        Me.FTempList = New System.Windows.Forms.ComboBox
        Me.SevenDayTestLabel = New System.Windows.Forms.Label
        Me.SevenDayTestText = New System.Windows.Forms.TextBox
        Me.SevenDayUnitLabel = New System.Windows.Forms.Label
        Me.FRunButton = New System.Windows.Forms.Button
        Me.FXButton = New System.Windows.Forms.Button
        Me.OutputLabel = New System.Windows.Forms.Label
        Me.SensitizedTimeLabel = New System.Windows.Forms.Label
        Me.SensitizedTimeText = New System.Windows.Forms.TextBox
```

```
Me.SenTimeUnitLabel = New System.Windows.Forms.Label
Me.FailureTimeLabel = New System.Windows.Forms.Label
Me.FailureTimeText = New System.Windows.Forms.TextBox
Me.FailTimeUnitLabel = New System.Windows.Forms.Label

'Input Parameters Label
Me.InputLabel.Location = New System.Drawing.Point(5, 20)
Me.InputLabel.AutoSize = True
Me.InputLabel.Font = New Font("Tahoma", 12)
Me.InputLabel.Text = "Input Parameters"

'Input; Alloy Type Label
Me.AlloyLabel.Location = New System.Drawing.Point(5, 50)
Me.AlloyLabel.AutoSize = True
Me.AlloyLabel.Font = New Font("Tahoma", 10)
Me.AlloyLabel.Text = "Alloy Type"

'Input; Alloy List
Me.FAlloyList.Location = New System.Drawing.Point(5, 70)
Me.FAlloyList.DropDownStyle = ComboBoxStyle.DropDownList
Me.FAlloyList.Items.Add("5083-H131")
Me.FAlloyList.Items.Add("5083-H116")
Me.FAlloyList.Items.Add("5083-H321")
Me.FAlloyList.Items.Add("5456-H116")
Me.FAlloyListEnable = False

'Input; Temp Label
Me.TempLabel.Location = New System.Drawing.Point(5, 110)
Me.TempLabel.AutoSize = True
Me.TempLabel.Font = New Font("Tahoma", 10)
Me.TempLabel.Text = "Climate Zone"

'Input; Temp List
Me.FTempList.Location = New System.Drawing.Point(5, 130)
Me.FTempList.DropDownStyle = ComboBoxStyle.DropDownList
Me.FTempList.Items.Add("Arid (70-120F)")
Me.FTempList.Items.Add("Tropic (60-110F)")
Me.FTempList.Items.Add("Temperate (50-100F)")
Me.FTempList.Items.Add("Cool (40-80F)")
Me.FTempListEnable = False

'Input; 7 Day Mass Lost Test Result Label
Me.SevenDayTestLabel.Location = New System.Drawing.Point(5, 170)
Me.SevenDayTestLabel.Size = New System.Drawing.Point(225, 40)
Me.SevenDayTestLabel.Font = New Font("Tahoma", 10)
```

```
    Me.SevenDayTestLabel.Text = "7 Day 100C Sensitized Sample ASTM G67 Mass
Loss Test Result"

    'Input; 7 Day Mass Lost Test Result Text
    Me.SevenDayTestText.Location = New System.Drawing.Point(5, 210)
    Me.SevenDayTestText.Size = New System.Drawing.Point(60, 20)
    SevenDayTestEnable = False

    'Input; 7 Day Mass Lost Test Result Unit Label
    Me.SevenDayUnitLabel.Location = New System.Drawing.Point(65, 210)
    Me.SevenDayUnitLabel.Size = New System.Drawing.Point(75, 20)
    Me.SevenDayUnitLabel.Font = New Font("Tahoma", 10)
    Me.SevenDayUnitLabel.Text = "mg/cm2"

    'Full Model Run Button
    Me.FRunButton.Location = New System.Drawing.Point(430, 195)
    Me.FRunButton.Size = New System.Drawing.Size(75, 20)
    Me.FRunButton.Enabled = False
    Me.FRunButton.Text = "Run"

    'Full Model Cancel Button
    Me.FXButton.Location = New System.Drawing.Point(430, 225)
    Me.FXButton.Size = New System.Drawing.Size(75, 20)
    Me.FXButton.Text = "Cancel"

    'Output Information Label
    Me.OutputLabel.Location = New System.Drawing.Point(235, 20)
    Me.OutputLabel.AutoSize = True
    Me.OutputLabel.Font = New Font("Tahoma", 12)
    Me.OutputLabel.Text = "Output Information"

    'Output; Sensitization Time Label
    Me.SensitizedTimeLabel.Location = New System.Drawing.Point(235, 50)
    Me.SensitizedTimeLabel.Size = New System.Drawing.Point(225, 40)
    Me.SensitizedTimeLabel.Font = New Font("Tahoma", 10)
    Me.SensitizedTimeLabel.Text = "Estimated Time to Threshold Sensitization (25
mg/cm2)"

    'Output; Sensitization Time Text
    Me.SensitizedTimeText.Location = New System.Drawing.Point(235, 90)
    Me.SensitizedTimeText.Size = New System.Drawing.Point(65, 20)
    Me.SensitizedTimeText.Enabled = False
    Me.SensitizedTimeText.Font = New Font("Tahoma", 8, FontStyle.Bold)

    'Output; Sensitization Time Unit Label
```

```
    Me.SenTimeUnitLabel.Location = New System.Drawing.Point(300, 90)
    Me.SenTimeUnitLabel.Size = New System.Drawing.Point(60, 20)
    Me.SenTimeUnitLabel.Font = New Font("Tahoma", 10)
    Me.SenTimeUnitLabel.Text = "Years"

    'Output; High Sensitization Time Label
    Me.FailureTimeLabel.Location = New System.Drawing.Point(235, 130)
    Me.FailureTimeLabel.Size = New System.Drawing.Point(225, 40)
    Me.FailureTimeLabel.Font = New Font("Tahoma", 10)
    Me.FailureTimeLabel.Text = "Estimated Time to High Sensitization (40
mg/cm2)"

    'Output; High Sensitization Time Text
    Me.FailureTimeText.Location = New System.Drawing.Point(235, 170)
    Me.FailureTimeText.Size = New System.Drawing.Point(65, 20)
    Me.FailureTimeText.Enabled = False
    Me.FailureTimeText.Font = New Font("Tahoma", 8, FontStyle.Bold)

    'Output; High Sensitization Time Unit Label
    Me.FailTimeUnitLabel = New System.Windows.Forms.Label
    Me.FailTimeUnitLabel.Location = New System.Drawing.Point(300, 170)
    Me.FailTimeUnitLabel.Size = New System.Drawing.Point(60, 20)
    Me.FailTimeUnitLabel.Font = New Font("Tahoma", 10)
    Me.FailTimeUnitLabel.Text = "Years"

    'Adds all relevant components to the Full Model Form
    FForm.AutoSize = True
    FForm.Text = "Full Sensitization Model Predicition"
    FForm.Controls.Add(Me.InputLabel)
    FForm.Controls.Add(Me.AlloyLabel)
    FForm.Controls.Add(Me.FAlloyList)
    FForm.Controls.Add(Me.TempLabel)
    FForm.Controls.Add(Me.FTempList)
    FForm.Controls.Add(Me.SevenDayTestLabel)
    FForm.Controls.Add(Me.SevenDayTestText)
    FForm.Controls.Add(Me.FRunButton)
    FForm.Controls.Add(Me.FXButton)
    FForm.Controls.Add(Me.OutputLabel)
    FForm.Controls.Add(Me.SensitizedTimeLabel)
    FForm.Controls.Add(Me.SensitizedTimeText)
    FForm.Controls.Add(Me.SenTimeUnitLabel)
    FForm.Controls.Add(Me.FailureTimeLabel)
    FForm.Controls.Add(Me.FailureTimeText)
    FForm.Controls.Add(Me.FailTimeUnitLabel)
    FForm.Controls.Add(Me.SevenDayUnitLabel)
```

```
        FForm.Show()

    End Sub

    ' Ensure Full Model Alloy Selection
    Private Sub FAlloyList_Enable(ByVal sender As Object, ByVal e As
System.EventArgs)    Handles FAlloyList.SelectedIndexChanged

        SensitizedTimeText.Text = ""
        FailureTimeText.Text = ""

        If 0 <= FAlloyList.SelectedIndex <= 3 Then
            FAlloyListEnable = True
        End If

        If FAlloyListEnable = True And FTempListEnable = True And
SevenDayTestEnable = True Then
            FRunButton.Enabled = True
        End If

    End Sub

    ' Ensure Full Model Temperature Selection
    Private Sub FTempList_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles FTempList.SelectedIndexChanged

        SensitizedTimeText.Text = ""
        FailureTimeText.Text = ""

        If 0 <= FTempList.SelectedIndex <= 3 Then
            FTempListEnable = True
        End If

        If FAlloyListEnable = True And FTempListEnable = True And
SevenDayTestEnable =         True Then
            FRunButton.Enabled = True
        End If

    End Sub

    ' Ensure Seven Day Test Data Entered
    Private Sub SevenDayTest_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles SevenDayTestText.TextChanged

        SensitizedTimeText.Text = ""
```

```
        FailureTimeText.Text = ""

        If Double.TryParse(SevenDayTestText.Text, 1) Then
            SevenDayTestEnable = True
        Else
            FRunButton.Enabled = False
            SevenDayTestEnable = False
        End If

        If FAlloyListEnable = True And FTempListEnable = True And
SevenDayTestEnable = True Then
            FRunButton.Enabled = True
        End If

    End Sub

    ' Full Model Run
    Private Sub FRunButton_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles FRunButton.Click

        Dim T As Double
        Dim Temp0 As Double
        Dim TempA As Double
        Dim ADs As Double
        Dim EaDs As Double
        Dim ADb As Double
        Dim EaDb As Double
        Dim ADm As Double
        Dim EaDm As Double
        Dim Ds As Double '%diffusion coefficient in transition layer
        Dim Db As Double '%(0.65e-4)*exp(-110500/(8.314*T))
        Dim Gamma As Double '% surface tension
        Dim Phi As Double '%contact angle of beta phase
        Dim Omega As Double '% molar volume
        Dim Epsilon As Double '% thickness of transition layer
        Dim Na As Double '% concentration of solute in matrix
        Dim Nb As Double '% concentration of solute in precipitate
        Dim Nab As Double '%equilibrium concentration
        Dim Ns As Double '%(Nb+Nab)/2;
        Dim Dm As Double '%diffusion coffic0.592ient in matrix
        Dim h As Double '%size of the grain
        Dim x0 As Double '%Radius of precipitate
        Dim w0 As Double '%Steps of time
        Dim Lambda As Double '% unit length
        Dim t0 As Double
```

```
Dim Ra0 As Double
Dim tz As Double
Dim Jm As Double '%Mg atoms flux to the grain boundary
Dim Rsu As Double
Dim Cosga As Double
Dim V0 As Double
Dim Gw0 As Double
Dim time As Double
Dim i As Integer
Dim Ra As Double
Dim Aori As Double
Dim nbi As Double
Dim V1 As Double
Dim dV As Double
Dim dR As Double
Dim Ra1 As Double
Dim DDB As Double
Dim d2Db As Double
Dim dA As Double
Dim d2A As Double
Dim Aori1 As Double
Dim Gw1 As Double
Dim ti As Double
Dim SS As Double
Dim Bi As Double
Dim BetaTheta As Double ' Continuity of beta phase
Dim SensitizedTime As Double
Dim SensitizedCheck = True
Dim FailureTime As Double
Dim GRate As Double ' Reaction rate of the Grain Boundary
Dim BRate As Double ' Reaction rate of the beta phase
Dim PRate As Double ' Reaction rate of pre beta phase
Dim PreBetaFraction As Double ' "Pre Beta" fraction of continious beta phase
Dim MLThetaCutoff As Double ' Continuity cutoff for model transition
Dim ML As Double ' Predicted Mass Loss
Dim A As Double
Dim CHL As Double
Dim CHT As Double
Dim j As Integer
Dim ani As Double
Dim anj As Double
Dim nj As Integer
Dim Sumnj As Double
Dim annj As Double
Dim nk As Integer
```

```
Dim Sumnk As Double
Dim ank As Double
Dim ti1 As Double
Dim ni As Integer
Dim Sumni As Double
Dim Jm0 As Double
Dim Sum0 As Double

If FTempList.SelectedIndex = 3 Then
   TempA = (26.7 + 4.4) / 2
   Temp0 = 273 + 4.4 + TempA
ElseIf FTempList.SelectedIndex = 2 Then
   TempA = (37.8 + 10.0) / 2
   Temp0 = 273 + 10 + TempA
ElseIf FTempList.SelectedIndex = 1 Then
   TempA = (43.3 + 15.6) / 2
   Temp0 = 273 + 15.6 + TempA
ElseIf FTempList.SelectedIndex = 0 Then
   TempA = (48.9 + 21.1) / 2
   Temp0 = 273 + 21.1 + TempA
End If

T = Temp0
ADs = 0.000045
EaDs = 104200
ADb = 0.000065
EaDb = 111500
ADm = 0.0000149
EaDm = 114000
Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition layer
Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
Gamma = 0.3 '% surface tension
Phi = 18.5 / 180 * PI '%contact angle of beta phase
Omega = 0.00001 '% molar volume
Epsilon = 0.0000000005 '% thickness of transition layer
Na = 5480.0 '% concentration of solute in matrix
Nb = 40000.0 '% concentration of solute in precipitate
Nab = 3250.0 '%equilibrium concentration
Ns = (Nb + Nab) / 2 '%(Nb+Nab)/2;
Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
h = 0.000001 '%size of the grain
x0 = 0.5 '%Radius of precipitate
w0 = 0.5 '%Steps of time
Lambda = 0.000000000004 '% unit length
```

```
    t0 = PI ^ (1 / 3) * Lambda ^ 2 / (Dm * Db * Db) ^ (1 / 3) * (Nb - Nab) ^ (2 / 3) /
(Na - Nab) ^ (2 / 3)
    Ra0 = x0 * Lambda
    tz = w0 * t0

    T = TempA * Sin(PI / 43200 * tz) + Temp0 '%temperature profile
    Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition layer
    Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
    Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
    t0 = PI ^ (1 / 3) * Lambda ^ 2 / (Dm * Db * Db) ^ (1 / 3) * (Nb - Nab) ^ (2 / 3) /
(Na - Nab) ^ (2 / 3)

    Jm = (Na - Nab) * Dm ^ 0.5 / (PI * tz) ^ 0.5 '%Mg atoms flux to the grain
boundary
    Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 * (4 * PI *
Db * tz - PI * Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
    Cosga = Cos(Phi) / Rsu
    V0 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
    Gw0 = tz ^ 0.5

    time = tz + 2 * t0
    i = 0
    Ra = (x0 + 1) * Lambda
    Aori = 4 * PI * (Db * time)
    nbi = 1

    GRate = 5 / (86400 * 0.5 * 2700)
    BRate = 45 / (86400 * 0.5 * 2700)
    PRate = (GRate + 2 * BRate) / 3
    PreBetaFraction = 0.5
    MLThetaCutoff = 1 / (1 + 2 * PreBetaFraction)

    'First Stage
    Do While (i < 250000000.0)

      If 25 < ML And SensitizedCheck = True Then
        SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
        SensitizedCheck = False
      End If

      If 40 < ML Then
        Exit Do
      End If
      T = TempA * Sin(PI / 43200 * time) + Temp0
```

```
        Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition
layer
        Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
        Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
        Jm = (Na - Nab) * Dm ^ 0.5 / (PI * time) ^ 0.5
        Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (Aori -
PI * Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
        If (4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (Aori - PI * Ra
^ 2) /  (2 * PI * Ra * Epsilon * Sin(Phi))) < 0 Then
          Rsu = (1 / 3) ^ 0.5
        End If

        Cosga = Cos(Phi) / Rsu
        V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
        dV = (V1 - V0) / 2 / t0
        dR = Gw0 * 4 * (Na - Nab) * Db * Dm ^ 0.5 / (Nb - Nab) / PI ^ 0.5 / Ra ^ 2 / V0 -
         Ra / 3 / V0 * dV
        Ra1 = dR * 2 * t0 + Ra
        DDB = EaDb * 20 * PI / 8.314 / (T ^ 2) / 43200 * Db * Cos(PI / 43200 * time)
        d2Db = EaDb * 20 * PI / 8.314 / 43200 * (-2 * Db * Cos(PI / 43200 * time) / T
^ 3 + 1 / T ^ 2 * DDB * Cos(PI / 43200 * time) - 1 / T ^ 2 * Db * PI / 43200 * Sin(PI /
43200 * time))
        dA = (4 * PI * Db + 4 * PI * time * DDB)
        d2A = 4 * PI * (DDB + 4 * PI * DDB + 4 * PI * time * d2Db)
        Aori1 = dA * 2 * t0 + 0.5 * d2A * (2 * t0) ^ 2 + Aori

        Gw1 = time ^ 0.5
        V0 = V1
        Ra = Ra1
        Aori = Aori1
        Gw0 = Gw1
        time = time + 2 * t0
        i = i + 1
        ti = time / 3600 / 24 / 15
        SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
        Bi = (Aori / PI) ^ 0.5 / 0.00000011283
        If Bi >= nbi Then
          Exit Do
        End If

        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
```

```
            ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
            ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
         * 0.5 *  2700
        End If

    Loop

    'Second stage
    A = 0.00000000000004
    Lambda = 0.0000000001 '% unit length
    t0 = PI ^ 3 * Lambda ^ 4 / A / Dm * (Nb - Nab) ^ 2 / (Na - Nab) ^ 2
    CHL = Ra / Lambda
    CHT = time / t0
    x0 = CHL '%Radius of precipitate
    w0 = CHT '%Steps of time
    Ra0 = x0 * Lambda
    tz = w0 * t0
    T = TempA * Sin(PI / 43200 * tz) + Temp0
    Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition layer
    Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
    Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
    t0 = PI ^ 3 * Lambda ^ 4 / A / Dm * (Nb - Nab) ^ 2 / (Na - Nab) ^ 2
    Jm = (Na - Nab) * Dm ^ 0.5 / (PI * tz) ^ 0.5
    Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 * (A - PI *
Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
    If (4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI * Ra ^ 2)
/ (2 *   PI * Ra * Epsilon * Sin(Phi))) < 0 Then
        Rsu = (1 / 3) ^ 0.5
    End If

    Cosga = Cos(Phi) / Rsu
    V0 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
    Gw0 = tz ^ (-0.5)
    time = tz + 2 * t0
    Ra = x0 * Lambda
    j = 0

    Do While (j < 30000000.0)

        If 25 < ML And SensitizedCheck = True Then
            SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
            SensitizedCheck = False
```

```
        End If

        If 40 < ML Then
            Exit Do
        End If

        T = TempA * Sin(PI / 43200 * time) + Temp0

        Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition
layer
        Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
        Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
        Jm = (Na - Nab) * Dm ^ 0.5 / (PI * time) ^ 0.5
        Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI *
         Ra ^    2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
        If (4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI * Ra ^
2) / (2 * PI * Ra * Epsilon * Sin(Phi))) < 0 Then
            Rsu = (1 / 3) ^ 0.5
        End If
        Cosga = Cos(Phi) / Rsu
        V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
        dV = (V1 - V0) / 2 / t0
        dR = Gw0 * A * (Na - Nab) * Dm ^ 0.5 / (Nb - Nab) / PI ^ 1.5 / Ra ^ 2 / V0 - Ra
/ 3 / V0 * dV
        Ra1 = dR * 2 * t0 + Ra
        Gw1 = time ^ (-0.5)
        V0 = V1
        Ra = Ra1
        Gw0 = Gw1
        time = time + 2 * t0
        j = j + 1
        ti = time / 3600 / 24 / 15
        SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
            ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
            ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
         * 0.5 *  2700
        End If

    Loop
```

```
'Third Stage
A = 0.00000000000004
Lambda = 0.000000000015 '% unit length
t0 = PI * Lambda ^ 3 * h / Dm / 4 / A * (Nb - Nab) / (Na - Nab)
x0 = Ra / Lambda '%Radius of precipitate
w0 = time / t0 '%Steps of time
Ra0 = x0 * Lambda
tz = w0 * t0
T = TempA * Sin(PI / 43200 * tz) + Temp0
Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition layer
Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
ni = 0
Sumni = 0

Do While (ni < 50)
   ani = Exp(-((2 * ni + 1) * PI / h) ^ 2 * Dm * tz)
   Sumni = Sumni + ani
   ni = ni + 1
Loop

Jm0 = 4 * (Na - Nab) * Dm / h * Sumni
Rsu = (((4 + 3 * Jm0 * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 * (A - PI *
Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
If (4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI * Ra ^ 2)
/ (2 * PI * Ra * Epsilon * Sin(Phi))) < 0 Then
   Rsu = (1 / 3) ^ 0.5
End If

Cosga = Cos(Phi) / Rsu
V0 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
j = 0
Sum0 = 0

Do While (j < 50)
   anj = Exp(-((2 * j + 1) * PI / h) ^ 2 * Dm * tz)
   Sum0 = Sum0 + anj
   j = j + 1
Loop

Gw0 = Sum0
time = tz + 100 * t0
Ra = (x0 + 1) * Lambda
i = 0
```

```
    Do While ML < 40

        If ML > 39 Then
            ML = ML
        End If
        If 25 < ML And SensitizedCheck = True Then
            SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
            SensitizedCheck = False
        End If

        T = TempA * Sin(PI / 43200 * time) + Temp0
        Ds = (ADs) * Exp(-EaDs / (8.314 * T)) '%diffusion coefficient in transition
layer
        Db = (ADb) * Exp(-EaDb / (8.314 * T)) '%(0.65e-4)*exp(-110500/(8.314*T))
        Dm = (ADm) * Exp(-EaDm / (8.314 * T)) '%diffusion coffic0.592ient in matrix
        nj = 0
        Sumnj = 0

        Do While (nj < 50)
            annj = Exp(-((2 * nj + 1) * PI / h) ^ 2 * Dm * time)
            Sumnj = Sumnj + annj
            nj = nj + 1
        Loop

        Jm = 4 * (Na - Nab) * Dm / h * Sumnj
        Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI *
Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
        If (4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI * Ra ^
2) / (2 * PI * Ra * Epsilon * Sin(Phi))) < 0 Then
            Rsu = (1 / 3) ^ 0.5
        End If

        Cosga = Cos(Phi) / Rsu
        V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
        dV = (V1 - V0) / 2 / t0
        dR = 4 * Gw0 * A * (Na - Nab) * Dm / (Nb - Nab) / PI / Ra ^ 2 / V0 / h - Ra / 3 /
V0 * Dv

        If dR < 0 Then
            dR = 0
        End If

        Ra1 = dR * 2 * t0 + Ra
        nk = 0
```

```
        Sumnk = 0

        Do While (nk < 50)
          ank = Exp(-((2 * nk + 1) * PI / h) ^ 2 * Dm * time)
          Sumnk = Sumnk + ank
          nk = nk + 1
        Loop

        Gw1 = Sumnk
        V0 = V1
        Ra = Ra1
        Gw0 = Gw1
        time = time + 100 * t0
        i = i + 1
        ti1 = time / 3600 / 24 / 15
        SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
          ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
          ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
* 0.5 *  2700
        End If

      Loop

      SensitizedTimeText.Text = SensitizedTime
      FailureTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
      FailureTimeText.Text = FailureTime

    End Sub

    ' Full Model Cancel Button
    Private Sub FXButton_Click(ByVal sender As Object, ByVal e As System.EventArgs)
         Handles FXButton.Click

      FForm.Close()

    End Sub

    'Setup the Remaining Service Form
```

```
    Friend WithEvents RForm As System.Windows.Forms.Form 'Remaining Service
Form
    Friend WithEvents RAlloyList As System.Windows.Forms.ComboBox 'Input; Alloy
List
    Friend RAlloyListEnable As Boolean 'Check if Alloy Selection is complete
    Friend WithEvents RTempList As System.Windows.Forms.ComboBox 'Input;
Temp List
    Friend RTempListEnable As Boolean 'Check if Temp Selection is complete
    Friend WithEvents MLTestLabel As System.Windows.Forms.Label 'Input; current
sample Mass Lost Test Result Label
    Friend WithEvents MLTestText As System.Windows.Forms.TextBox 'Input;
current sample Mass Lost Test Result Text
    Friend WithEvents MLTestUnitLabel As System.Windows.Forms.Label 'Input;
current sample Mass Lost Test Result Unit Label
    Friend MLTestEnable As Boolean 'Check if current sample Mass Lost Test Result is
inputted
    Friend WithEvents RRunButton As System.Windows.Forms.Button 'Remaining
Service Model Run Button
    Friend WithEvents RXButton As System.Windows.Forms.Button 'Remaining
Service Model Cancel Button

    Private Sub RModel(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles RButton.Click

        ' Format the Remaining Service Form
        Me.RForm = New System.Windows.Forms.Form
        Me.InputLabel = New System.Windows.Forms.Label
        Me.AlloyLabel = New System.Windows.Forms.Label
        Me.RAlloyList = New System.Windows.Forms.ComboBox
        Me.TempLabel = New System.Windows.Forms.Label
        Me.RTempList = New System.Windows.Forms.ComboBox
        Me.MLTestLabel = New System.Windows.Forms.Label
        Me.MLTestText = New System.Windows.Forms.TextBox
        Me.MLTestUnitLabel = New System.Windows.Forms.Label
        Me.RRunButton = New System.Windows.Forms.Button
        Me.RXButton = New System.Windows.Forms.Button
        Me.OutputLabel = New System.Windows.Forms.Label
        Me.SensitizedTimeLabel = New System.Windows.Forms.Label
        Me.SensitizedTimeText = New System.Windows.Forms.TextBox
        Me.SenTimeUnitLabel = New System.Windows.Forms.Label
        Me.FailureTimeLabel = New System.Windows.Forms.Label
        Me.FailureTimeText = New System.Windows.Forms.TextBox
        Me.FailTimeUnitLabel = New System.Windows.Forms.Label

        'Input Parameters Label
```

```
Me.InputLabel.Location = New System.Drawing.Point(5, 20)
Me.InputLabel.AutoSize = True
Me.InputLabel.Font = New Font("Tahoma", 12)
Me.InputLabel.Text = "Input Parameters"

'Input; Alloy Type Label
Me.AlloyLabel.Location = New System.Drawing.Point(5, 50)
Me.AlloyLabel.AutoSize = True
Me.AlloyLabel.Font = New Font("Tahoma", 10)
Me.AlloyLabel.Text = "Alloy Type"

'Input; Alloy List
Me.RAlloyList.Location = New System.Drawing.Point(5, 70)
Me.RAlloyList.DropDownStyle = ComboBoxStyle.DropDownList
Me.RAlloyList.Items.Add("5083-H131")
Me.RAlloyList.Items.Add("5083-H116")
Me.RAlloyList.Items.Add("5083-H321")
Me.RAlloyList.Items.Add("5456-H116")
Me.RAlloyListEnable = False

'Input; Temp Label
Me.TempLabel.Location = New System.Drawing.Point(5, 110)
Me.TempLabel.AutoSize = True
Me.TempLabel.Font = New Font("Tahoma", 10)
Me.TempLabel.Text = "Climate Zone"

'Input; Temp List
Me.RTempList.Location = New System.Drawing.Point(5, 130)
Me.RTempList.DropDownStyle = ComboBoxStyle.DropDownList
Me.RTempList.Items.Add("Arid (70-120F)")
Me.RTempList.Items.Add("Tropic (60-110F)")
Me.RTempList.Items.Add("Temperate (50-100F)")
Me.RTempList.Items.Add("Cool (40-80F)")
Me.RTempListEnable = False

'Input; current sample Mass Lost Test Result Label
Me.MLTestLabel.Location = New System.Drawing.Point(5, 170)
Me.MLTestLabel.Size = New System.Drawing.Point(210, 40)
Me.MLTestLabel.Font = New Font("Tahoma", 10)
Me.MLTestLabel.Text = "ASTM G67 Mass Loss Test Result  For Current Sample"

'Input; current sample Mass Lost Test Result Text
Me.MLTestText.Location = New System.Drawing.Point(5, 210)
Me.MLTestText.Size = New System.Drawing.Point(60, 20)
MLTestEnable = False
```

```
'Input; current sample Mass Lost Test Result Unit Label
Me.MLTestUnitLabel.Location = New System.Drawing.Point(65, 210)
Me.MLTestUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.MLTestUnitLabel.Font = New Font("Tahoma", 10)
Me.MLTestUnitLabel.Text = "mg/cm2"

'Remaining Service Model Run Button
Me.RRunButton.Location = New System.Drawing.Point(365, 215)
Me.RRunButton.Size = New System.Drawing.Size(75, 20)
Me.RRunButton.Enabled = False
Me.RRunButton.Text = "Run"

'Remaining Service Model Cancel Button
Me.RXButton.Location = New System.Drawing.Point(365, 245)
Me.RXButton.Size = New System.Drawing.Size(75, 20)
Me.RXButton.Text = "Cancel"

'Output Information Label
Me.OutputLabel.Location = New System.Drawing.Point(225, 20)
Me.OutputLabel.AutoSize = True
Me.OutputLabel.Font = New Font("Tahoma", 12)
Me.OutputLabel.Text = "Output Information"

'Output; Sensitization Time Label
Me.SensitizedTimeLabel.Location = New System.Drawing.Point(225, 50)
Me.SensitizedTimeLabel.Size = New System.Drawing.Point(235, 40)
Me.SensitizedTimeLabel.Font = New Font("Tahoma", 10)
Me.SensitizedTimeLabel.Text = "Estimated Time Remaining to Threshold
Sensitization  (25 mg/cm2)"

'Output; Sensitization Time Text
Me.SensitizedTimeText.Location = New System.Drawing.Point(225, 90)
Me.SensitizedTimeText.Size = New System.Drawing.Point(65, 20)
Me.SensitizedTimeText.Enabled = False
Me.SensitizedTimeText.Font = New Font("Tahoma", 8, FontStyle.Bold)

'Output; Sensitization Time Unit Label
Me.SenTimeUnitLabel.Location = New System.Drawing.Point(290, 90)
Me.SenTimeUnitLabel.Size = New System.Drawing.Point(60, 20)
Me.SenTimeUnitLabel.Font = New Font("Tahoma", 10)
Me.SenTimeUnitLabel.Text = "Years"

'Output; High Sensitization Time Label
Me.FailureTimeLabel.Location = New System.Drawing.Point(225, 130)
```

```
        Me.FailureTimeLabel.Size = New System.Drawing.Point(215, 40)
        Me.FailureTimeLabel.Font = New Font("Tahoma", 10)
        Me.FailureTimeLabel.Text = "Estimated Time Remaining to High Sensitization
(40     mg/cm2)"

        'Output; High Sensitization Time Text
        Me.FailureTimeText.Location = New System.Drawing.Point(225, 170)
        Me.FailureTimeText.Size = New System.Drawing.Point(65, 20)
        Me.FailureTimeText.Enabled = False
        Me.FailureTimeText.Font = New Font("Tahoma", 8, FontStyle.Bold)

        'Output; High Sensitization Time Unit Label
        Me.FailTimeUnitLabel = New System.Windows.Forms.Label
        Me.FailTimeUnitLabel.Location = New System.Drawing.Point(290, 170)
        Me.FailTimeUnitLabel.Size = New System.Drawing.Point(60, 20)
        Me.FailTimeUnitLabel.Font = New Font("Tahoma", 10)
        Me.FailTimeUnitLabel.Text = "Years"

        'Adds all relevant components to the Remaining Service Model Form
        RForm.AutoSize = True
        RForm.Text = "Remaining Service Prediction"
        RForm.Controls.Add(Me.InputLabel)
        RForm.Controls.Add(Me.AlloyLabel)
        RForm.Controls.Add(Me.RAlloyList)
        RForm.Controls.Add(Me.TempLabel)
        RForm.Controls.Add(Me.RTempList)
        RForm.Controls.Add(Me.MLTestLabel)
        RForm.Controls.Add(Me.MLTestText)
        RForm.Controls.Add(Me.RRunButton)
        RForm.Controls.Add(Me.RXButton)
        RForm.Controls.Add(Me.OutputLabel)
        RForm.Controls.Add(Me.SensitizedTimeLabel)
        RForm.Controls.Add(Me.SensitizedTimeText)
        RForm.Controls.Add(Me.SenTimeUnitLabel)
        RForm.Controls.Add(Me.FailureTimeLabel)
        RForm.Controls.Add(Me.FailureTimeText)
        RForm.Controls.Add(Me.FailTimeUnitLabel)
        RForm.Controls.Add(Me.MLTestUnitLabel)
        RForm.Show()

    End Sub

    ' Ensure Remaining Service Alloy Selection
    Private Sub RAlloyList_Enable(ByVal sender As Object, ByVal e As
System.EventArgs)    Handles RAlloyList.SelectedIndexChanged
```

```
        SensitizedTimeText.Text = ""
        FailureTimeText.Text = ""

        If 0 <= RAlloyList.SelectedIndex <= 3 Then
            RAlloyListEnable = True

        End If

        If RAlloyListEnable = True And RTempListEnable = True And MLTestEnable =
True Then
            RRunButton.Enabled = True
        End If

    End Sub

    ' Ensure Remaining Service Temperature Selection
    Private Sub RTempList_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles RTempList.SelectedIndexChanged

        SensitizedTimeText.Text = ""
        FailureTimeText.Text = ""

        If 0 <= RTempList.SelectedIndex <= 3 Then
            RTempListEnable = True

        End If

        If RAlloyListEnable = True And RTempListEnable = True And MLTestEnable =
True Then
            RRunButton.Enabled = True
        End If

    End Sub

    ' Ensure Mass Loss Test Data Entered
    Private Sub MLTest_Enable(ByVal sender As Object, ByVal e As System.EventArgs)
Handles MLTestText.TextChanged

        SensitizedTimeText.Text = ""
        FailureTimeText.Text = ""

        If Double.TryParse(MLTestText.Text, 1) Then
            MLTestEnable = True
        Else
```

```
            RRunButton.Enabled = False
            MLTestEnable = False
        End If

        If RAlloyListEnable = True And RTempListEnable = True And MLTestEnable =
True Then
            RRunButton.Enabled = True
        End If

    End Sub

    ' Remaining Service Run
    Private Sub RRunButton_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles RRunButton.Click

        Dim CurrentMLResult = Double.Parse(MLTestText.Text)
        Dim CurrentTime As Double
        Dim CurrentMLCheck = True

        ' Define all variables
        Dim T As Double ' Temperature
        Dim Ds As Double ' Diffusion Coefficient in the transition layer
        Dim Db As Double ' Diffusion Coefficient in the beta phase
        Dim Gamma As Double ' Surface Tension
        Dim Phi As Double 'Precipitate Contact Angle
        Dim Omega As Double ' Molar Volume
        Dim Epsilon As Double ' Transition layer thickness
        Dim Na As Double ' Concentration in matrix
        Dim Nb As Double ' Concentration in beta phase
        Dim Nab As Double ' Equilibrium concentration
        Dim Ns As Double
        Dim Dm As Double ' Diffusion Coefficient in the matrix
        Dim x0 As Double ' Beta phase radius
        Dim w0 As Double ' Time steps
        Dim Lambda As Double ' Unit Length
        Dim t0 As Double
        Dim Ra0 As Double
        Dim tz As Double
        Dim Jm As Double
        Dim Rsu As Double
        Dim Cosga As Double
        Dim V0 As Double
        Dim Gw0 As Double
        Dim time As Double
        Dim Ra As Double ' Length of beta phase / 2
```

```
Dim w As Double
Dim dx As Double
Dim dV As Double
Dim V1 As Double
Dim Gw1 As Double
Dim x1 As Double
Dim SS As Double
Dim lef As Double
Dim L As Double
Dim BetaTheta As Double ' Continuity of beta phase
Dim SensitizedTime As Double
Dim SensitizedCheck = True
Dim FailureTime As Double
Dim GRate As Double ' Reaction rate of the Grain Boundary
Dim BRate As Double ' Reaction rate of the beta phase
Dim PRate As Double ' Reaction rate of pre beta phase
Dim PreBetaFraction As Double ' "Pre Beta" fraction of continious beta phase
Dim MLThetaCutoff As Double ' Continuity cutoff for model transition
Dim ML As Double ' Predicted Mass Loss
Dim i = 1

If RTempList.SelectedIndex = 0 Then
  T = 273 + 70
ElseIf RTempList.SelectedIndex = 1 Then
  T = 273 + 60
ElseIf RTempList.SelectedIndex = 2 Then
  T = 273 + 50
ElseIf RTempList.SelectedIndex = 3 Then
  T = 273 + 40
End If

Ds = (0.000045) * Exp(-104200 / (8.314 * T))
Db = (0.000065) * Exp(-111500 / (8.314 * T))
Gamma = 0.3
Phi = 18.5 / 180 * PI
Omega = 0.00001
Epsilon = 0.0000000005
Na = 5480.0
Nb = 40000.0
Nab = 3250.0
Ns = (Nb + Nab) / 2
Dm = (0.0000149) * Exp(-113000 / (8.314 * T))
Lambda = 0.000000000001
t0 = PI ^ (1 / 3) * Lambda ^ 2 / (Dm * Db * Db) ^ (1 / 3) * (Nb - Nab) ^ (2 / 3) /
(Na - Nab) ^ (2 / 3)
```

```
    x0 = 0.5
    w0 = 0.5
    tz = w0 * t0
    Ra = x0 * Lambda
    GRate = 5 / (86400 * 0.5 * 2700)
    BRate = 45 / (86400 * 0.5 * 2700)
    PRate = (GRate + 2 * BRate) / 3
    PreBetaFraction = 0.13
    MLThetaCutoff = 1 / (1 + 2 * PreBetaFraction)
    Cosga = Cos(Phi) / Rsu
    V0 = Tan(Phi) / (1 - 1 / (1 + Cosga) ^ 2)
    Gw0 = w0 ^ 0.5
    Ra0 = x0 * Lambda
    time = tz + 2 * t0
    Jm = (Na - Nab) * Dm ^ 0.5 / (PI * tz) ^ 0.5
    Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 * (4 * PI *
Db * tz - PI * Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5

    'First Stage
    Do Until i = 100000000
      If 40 < ML Then
        Exit Do
      End If

      If 25 < ML And SensitizedCheck = True Then
        SensitizedTime = Math.Round(time / 3600 / 24 / 30, 1)
        SensitizedCheck = False
      End If

      If CurrentMLResult < ML And CurrentMLCheck = True Then
        CurrentTime = Math.Round(time / 3600 / 24 / 30, 1)
        CurrentMLCheck = False
      End If

      w = w0 + 1 '%the number "1" in this line actually is the time step
      Ra = x0 * Lambda
      time = w * t0
      Jm = (Na - Nab) * Dm ^ 0.5 / (PI * time) ^ 0.5
      Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (4 * PI *
Db * T - PI * Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
      Cosga = Cos(Phi) / Rsu
      V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
      dV = (V1 - V0) / 1
      dx = 4 * Gw0 / x0 ^ 2 / V0 - x0 / 3 / V0 * dV
      x1 = dx * 1 + x0
```

```
        Gw1 = time ^ 0.5
        V0 = V1
        x0 = x1
        Gw0 = Gw1
        w0 = w
        SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
        L = 2 * (Db * time) ^ 0.5

        If L >= (0.00000011283) Then
          Exit Do
        End If

        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
          ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
          ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
* 0.5 *  2700
        End If

        i = i + 1

      Loop

      Dim CHD = Ra / 0.00000000000002

      'Second stage
      Dim A = 0.00000000000004
      Dim Ds2 = (0.000045) * Exp(-104200 / (8.314 * T)) '%diffusion coefficient in
transition layer
      Dim Db2 = (0.000065) * Exp(-111500 / (8.314 * T)) '%(0.65e-4)*exp(-
110500/(R*T))
      Dim Dm2 = (0.0000149) * Exp(-113000 / (8.314 * T)) ' %125500diffusion
coffic0.592ient in matrix
      Lambda = 0.00000000000002 '% unit length
      t0 = PI ^ 3 * Lambda ^ 2 / Dm2 * (Nb - Nab) ^ 2 / (Na - Nab) ^ 2
      Dim CHT = time / t0
      x0 = CHD '%Radius of precipitate
      w0 = CHT '%Steps of time
      Ra0 = x0 * Lambda
      tz = w0 * t0
      Jm = (Na - Nab) * Dm2 ^ 0.5 / (PI * tz) ^ 0.5
```

```
        Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds2 * Ns * Gamma * Omega) * Ra0 ^ 2 * (A - PI *
Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
        Cosga = Cos(Phi) / Rsu
        V0 = Tan(Phi) / (1 - 1 / (1 + Cosga) ^ 2)
        Gw0 = A / (Lambda ^ 2) / (w0 ^ 0.5)
        time = tz + 2 * t0
        Ra = x0 * Lambda
        i = 0

        Do While (i < 2200000000.0)
            If 40 < ML Then
                Exit Do
            End If

            If 25 < ML And SensitizedCheck = True Then
                SensitizedTime = Math.Round(time / 3600 / 24 / 30, 1)
                SensitizedCheck = False
            End If

            If CurrentMLResult < ML And CurrentMLCheck = True Then
                CurrentTime = Math.Round(time / 3600 / 24 / 30, 1)
                CurrentMLCheck = False
            End If

            w = w0 + 1
            Ra = x0 * Lambda
            time = w * t0
            Jm = (Na - Nab) * Dm2 ^ 0.5 / (PI * time) ^ 0.5
            Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds2 * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI
* Ra ^  2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
            Cosga = Cos(Phi) / Rsu
            V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
            dV = (V1 - V0) / 1
            dx = Gw0 / x0 ^ 2 / V0 - x0 / 3 / V0 * dV
            x1 = dx * 1 + x0
            Gw1 = A / (Lambda ^ 2) / (w ^ 0.5)
            V0 = V1
            x0 = x1
            Gw0 = Gw1
            w0 = w
            i = i + 1
            SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
            lef = time / 1296000

            If lef >= 40 Then
```

```
            Exit Do
         End If

         BetaTheta = Ra / (1 * 10 ^ -7)

         If BetaTheta < MLThetaCutoff Then
            ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
         Else
            ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
          * 0.5 *  2700
         End If

      Loop

      'Third stage
      Dim h = 0.000001 '%grain size of Al (average)
      Lambda = 0.00000000002 '% unit length (step length)
      t0 = PI * h * Lambda ^ 3 / Dm / A * (Nb - Nab) / (Na - Nab) '%time step(step
length of time)
      x0 = Ra / Lambda '%Radius of precipitate
      w0 = time / t0 '%Steps of time
      Ra0 = x0 * Lambda '%Initial value of length, should be the end of value of last
stage
      tz = w0 * t0 '% Initial value of time, should be the same as the end value of last
stage
      Dim ni = 0
      Dim Sumni = 0
      Dim ani As Double

      Do While ni < 50
         ani = Exp(-((2 * ni + 1) * PI / h) ^ 2 * Dm * tz)
         Sumni = Sumni + ani
         ni = ni + 1
      Loop

      Dim Jm0 = 4 * (Na - Nab) * Dm / h * Sumni 'the aim of the above few lines is to
calculate the solute flux of Mg to the grain boundary
      Dim Rsu0 = (((4 + 3 * Jm0 * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 *
(A - PI * Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
      Cosga = Cos(Phi) / Rsu0
      V0 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
      Dim j = 0
      Dim Sum0 = 0
```

```
Gw0 = Sumni
i = 0
Dim ict3 = 16
Dim nj As Double
Dim Sumnj As Double
Dim anj As Double
Dim RR As Double

Do While i < 300000000.0

  If 40 < ML Then
    Exit Do
  End If

  If 25 < ML And SensitizedCheck = True Then
    SensitizedTime = Math.Round(time / 3600 / 24 / 30, 1)
    SensitizedCheck = False
  End If

  If CurrentMLResult < ML And CurrentMLCheck = True Then
    CurrentTime = Math.Round(time / 3600 / 24 / 30, 1)
    CurrentMLCheck = False
  End If

  w = w0 + 2
  Ra = x0 * Lambda
  time = w * t0
  nj = 0
  Sumnj = 0

  Do While nj < 50
    anj = Exp(-((2 * nj + 1) * PI / h) ^ 2 * Dm * T)
    Sumnj = Sumnj + anj
    nj = nj + 1
  Loop

  Jm = 4 * (Na - Nab) * Dm / h * Sumnj
  Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI *
Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
  Cosga = Cos(Phi) / Rsu
  V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
  dV = (V1 - V0) / 2
  dx = 4 * Gw0 / (x0 ^ 2) / V0 - x0 / 3 / V0 * dV
  x1 = dx * 2 + x0
  Gw1 = Sumnj
```

```
        V0 = V1
        x0 = x1
        Gw0 = Gw1
        w0 = w
        i = i + 1
        RR = x0 * Lambda
        SS = Tan(Phi) * Cosga / (1 + Cosga) * x0 * Lambda
        lef = time / 1296000

        If RR > 0.0000001 Then
          Exit Do
        End If
        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
          ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
          ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
* 0.5 *  2700
        End If

      Loop

      If CurrentMLResult >= 25 Then
        SensitizedTimeText.Text = "N/A"
        SensitizedTimeText.Refresh()
      Else
        SensitizedTimeText.Text = Math.Round(SensitizedTime - CurrentTime, 1)
        SensitizedTimeText.Refresh()
      End If

      FailureTime = Math.Round(time / 3600 / 24 / 30, 1)

      If CurrentMLResult >= 40 Then
        FailureTimeText.Text = "N/A"
        FailureTimeText.Refresh()
      Else
        FailureTimeText.Text = Math.Round(FailureTime - CurrentTime, 1)
        FailureTimeText.Refresh()
      End If

    End Sub
```

```
    ' Remaining Service Cancel Button
    Private Sub RXButton_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles RXButton.Click

        RForm.Close()

    End Sub

    'Setup the Advanced Model Form
    Friend WithEvents AForm As System.Windows.Forms.Form 'Advanced Model
Form
    Friend WithEvents AAlloyList As System.Windows.Forms.ComboBox 'Input; Alloy
List
    Friend AAlloyListEnable As Boolean 'Check if Alloy Selection is complete
    Friend WithEvents ACTempBox As System.Windows.Forms.CheckBox 'Input;
Contast Temp Selection
    Friend ACTempBoxEnable As Boolean 'Check if Constant Temp in selected
    Friend WithEvents ACTempText As System.Windows.Forms.TextBox 'Input;
Contast Temp
    Friend WithEvents ACTempUnitLabel As System.Windows.Forms.Label 'Input;
Contast Temp Unit Label
    Friend ACTempEnable As Boolean 'Check if Constant Temp in inputted
    Friend WithEvents ACycTempBox As System.Windows.Forms.CheckBox 'Input;
Cyclic  Temp Selection
    Friend ACycTempBoxEnable As Boolean 'Check if Cyclic Temp in selected
    Friend WithEvents ACycTempLabel As System.Windows.Forms.Label 'Input;
Cyclic Temp   Label
    Friend WithEvents AWinTempLabel As System.Windows.Forms.Label 'Input;
Cyclic  Winter Temp Label
    Friend WithEvents AWinTempText As System.Windows.Forms.TextBox 'Input;
Cyclic  Winter Temp Text
    Friend WithEvents AWinTempUnitLabel As System.Windows.Forms.Label 'Input;
Cyclic  Winter Temp Unit Label
    Friend AWinTempEnable As Boolean 'Check if Cyclic Winter Temp in inputted
    Friend WithEvents ASprTempLabel As System.Windows.Forms.Label 'Input;
Cyclic  Spring Temp Label
    Friend WithEvents ASprTempText As System.Windows.Forms.TextBox 'Input;
Cyclic  Spring Temp Text
    Friend WithEvents ASprTempUnitLabel As System.Windows.Forms.Label 'Input;
Cyclic  Spring Temp Unit Label
    Friend ASprTempEnable As Boolean 'Check if Cyclic Spring Temp in inputted
    Friend WithEvents ASumTempLabel As System.Windows.Forms.Label 'Input;
Cyclic  Summer Temp Label
    Friend WithEvents ASumTempText As System.Windows.Forms.TextBox 'Input;
Cyclic  Summer Temp Text
```

```
   Friend WithEvents ASumTempUnitLabel As System.Windows.Forms.Label 'Input;
Cyclic  Summer Temp Unit Label
   Friend ASumTempEnable As Boolean 'Check if Cyclic Summer Temp in inputted
   Friend WithEvents AFalTempLabel As System.Windows.Forms.Label 'Input; Cyclic
Fall Temp Label
   Friend WithEvents AFalTempText As System.Windows.Forms.TextBox 'Input;
Cyclic Fall Temp Text
   Friend WithEvents AFalTempUnitLabel As System.Windows.Forms.Label 'Input;
Cyclic  Fall Temp Unit Label
   Friend AFalTempEnable As Boolean 'Check if Cyclic Fall Temp in inputted
   Friend WithEvents ABulkConcLabel As System.Windows.Forms.Label 'Input; Bulk
Magnesium Concentration Label
   Friend WithEvents ABulkConcText As System.Windows.Forms.TextBox 'Input;
Bulk Magnesium Concentration Text
   Friend WithEvents ABulkConcUnitLabel As System.Windows.Forms.Label 'Input;
Bulk Magnesium Concentration Unit Label
   Friend ABulkConcEnable As Boolean 'Check if Bulk Magnesium Concentration in
inputted
   Friend WithEvents AAdvancedBox As System.Windows.Forms.CheckBox 'Input;
Advanced Parameters Selection
   Friend WithEvents AAdvancedLabel As System.Windows.Forms.Label 'Input;
Advanced Parameters Selection Label
   Friend AAdvancedEnable As Boolean 'Check if Advanced Parameters are selected
   Friend WithEvents ALine As System.Windows.Forms.Label 'Advanced Parameters
Separation Line
   Friend WithEvents ABulkDifLabel As System.Windows.Forms.Label 'Advanced
Parameters Input; Bulk Magnesium Diffusion Label
   Friend WithEvents ABulkDifText As System.Windows.Forms.TextBox 'Advanced
Parameters Input; Bulk Magnesium Diffusion Text
   Friend WithEvents ABulkDifUnitLabel As System.Windows.Forms.Label
'Advanced Parameters Input; Bulk Magnesium Diffusion Unit Label
   Friend ABulkDifEnable As Boolean 'Check if Bulk Magnesium Diffusion in inputted
   Friend WithEvents AGBDifLabel As System.Windows.Forms.Label 'Advanced
Parameters Input; Grain Boundary Magnesium Diffusion Label
   Friend WithEvents AGBDifText As System.Windows.Forms.TextBox 'Advanced
Parameters Input; Grain Boundary Magnesium Diffusion Text
   Friend WithEvents AGBDifUnitLabel As System.Windows.Forms.Label 'Advanced
Parameters Input; Grain Boundary Magnesium Diffusion Unit Label
   Friend AGBDifEnable As Boolean 'Check if Grain Boundary Magnesium Diffusion
in inputted
   Friend WithEvents AIntDifLabel As System.Windows.Forms.Label 'Advanced
Parameters Input; Interface Magnesium Diffusion Label
   Friend WithEvents AIntDifText As System.Windows.Forms.TextBox 'Advanced
Parameters Input; Interface Magnesium Diffusion Text
```

```
Friend WithEvents AIntDifUnitLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Interface Magnesium Diffusion Unit Label
Friend AIntDifEnable As Boolean 'Check if Interface Magnesium Diffusion in inputted
Friend WithEvents NucDenLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Nucleation Density Label
Friend WithEvents NucDenText As System.Windows.Forms.TextBox 'Advanced Parameters Input; Nucleation Density Text
Friend WithEvents NucDenUnitLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Nucleation Density Unit Label
Friend NucDenEnable As Boolean 'Check if Nucleation Density in inputted
Friend WithEvents ContAngLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Contact Angle Label
Friend WithEvents ContAngText As System.Windows.Forms.TextBox 'Advanced Parameters Input; Contact Angle Text
Friend WithEvents ContAngUnitLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Contact Angle Unit Label
Friend ContAngEnable As Boolean 'Check if Contact Angle in inputted
Friend WithEvents SurfTenLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Surface Tension Label
Friend WithEvents SurfTenText As System.Windows.Forms.TextBox 'Advanced Parameters Input; Surface Tension Text
Friend WithEvents SurfTenUnitLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Surface Tension Unit Label
Friend SurfTenEnable As Boolean 'Check if Surface Tension in inputted
Friend WithEvents ABetaConcLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Beta Phase Magnesium Concentration Label
Friend WithEvents ABetaConcText As System.Windows.Forms.TextBox 'Advanced Parameters Input; Beta Phase Magnesium Concentration Text
Friend WithEvents ABetaConcUnitLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Beta Phase Magnesium Concentration Unit Label
Friend ABetaConcEnable As Boolean 'Check if Beta Phase Magnesium Concetration in inputted
Friend WithEvents AEqConcLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Beta Phase Equilibrium Magnesium Concentration Label
Friend WithEvents AEqConcText As System.Windows.Forms.TextBox 'Advanced Parameters Input; Beta Phase Equilibrium Magnesium Concentration Text
Friend WithEvents AEqConcUnitLabel As System.Windows.Forms.Label 'Advanced Parameters Input; Beta Phase Equilibrium Magnesium Concentration Unit Label
Friend AEqConcEnable As Boolean 'Check if Equilibrium Magnesium Concetration in inputted
Friend WithEvents ARunButton As System.Windows.Forms.Button 'Advanced Model Run Button
```

```
    Friend WithEvents AXButton As System.Windows.Forms.Button 'Advanced Model
Cancel Button


    Private Sub AModel(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles AButton.Click

        ' Format the Advanced Model Form
        Me.AForm = New System.Windows.Forms.Form
        Me.InputLabel = New System.Windows.Forms.Label
        Me.AlloyLabel = New System.Windows.Forms.Label
        Me.AAlloyList = New System.Windows.Forms.ComboBox
        Me.ACTempBox = New System.Windows.Forms.CheckBox
        Me.TempLabel = New System.Windows.Forms.Label
        Me.ACTempText = New System.Windows.Forms.TextBox
        Me.ACTempUnitLabel = New System.Windows.Forms.Label
        Me.ACycTempBox = New System.Windows.Forms.CheckBox
        Me.ACycTempLabel = New System.Windows.Forms.Label
        Me.AWinTempLabel = New System.Windows.Forms.Label
        Me.AWinTempText = New System.Windows.Forms.TextBox
        Me.AWinTempUnitLabel = New System.Windows.Forms.Label
        Me.ASprTempLabel = New System.Windows.Forms.Label
        Me.ASprTempText = New System.Windows.Forms.TextBox
        Me.ASprTempUnitLabel = New System.Windows.Forms.Label
        Me.ASumTempLabel = New System.Windows.Forms.Label
        Me.ASumTempText = New System.Windows.Forms.TextBox
        Me.ASumTempUnitLabel = New System.Windows.Forms.Label
        Me.AFalTempLabel = New System.Windows.Forms.Label
        Me.AFalTempText = New System.Windows.Forms.TextBox
        Me.AFalTempUnitLabel = New System.Windows.Forms.Label
        Me.ABulkConcLabel = New System.Windows.Forms.Label
        Me.ABulkConcText = New System.Windows.Forms.TextBox
        Me.ABulkConcUnitLabel = New System.Windows.Forms.Label
        Me.AAdvancedBox = New System.Windows.Forms.CheckBox
        Me.AAdvancedLabel = New System.Windows.Forms.Label
        Me.ALine = New System.Windows.Forms.Label
        Me.ABulkDifLabel = New System.Windows.Forms.Label
        Me.ABulkDifText = New System.Windows.Forms.TextBox
        Me.ABulkDifUnitLabel = New System.Windows.Forms.Label
        Me.AGBDifLabel = New System.Windows.Forms.Label
        Me.AGBDifText = New System.Windows.Forms.TextBox
        Me.AGBDifUnitLabel = New System.Windows.Forms.Label
        Me.AIntDifLabel = New System.Windows.Forms.Label
        Me.AIntDifText = New System.Windows.Forms.TextBox
        Me.AIntDifUnitLabel = New System.Windows.Forms.Label
```

```
Me.NucDenLabel = New System.Windows.Forms.Label
Me.NucDenText = New System.Windows.Forms.TextBox
Me.NucDenUnitLabel = New System.Windows.Forms.Label
Me.ContAngLabel = New System.Windows.Forms.Label
Me.ContAngText = New System.Windows.Forms.TextBox
Me.ContAngUnitLabel = New System.Windows.Forms.Label
Me.SurfTenLabel = New System.Windows.Forms.Label
Me.SurfTenText = New System.Windows.Forms.TextBox
Me.SurfTenUnitLabel = New System.Windows.Forms.Label
Me.ABetaConcLabel = New System.Windows.Forms.Label
Me.ABetaConcText = New System.Windows.Forms.TextBox
Me.ABetaConcUnitLabel = New System.Windows.Forms.Label
Me.AEqConcLabel = New System.Windows.Forms.Label
Me.AEqConcText = New System.Windows.Forms.TextBox
Me.AEqConcUnitLabel = New System.Windows.Forms.Label
Me.ARunButton = New System.Windows.Forms.Button
Me.AXButton = New System.Windows.Forms.Button
Me.OutputLabel = New System.Windows.Forms.Label
Me.SensitizedTimeLabel = New System.Windows.Forms.Label
Me.SensitizedTimeText = New System.Windows.Forms.TextBox
Me.SenTimeUnitLabel = New System.Windows.Forms.Label
Me.FailureTimeLabel = New System.Windows.Forms.Label
Me.FailureTimeText = New System.Windows.Forms.TextBox
Me.FailTimeUnitLabel = New System.Windows.Forms.Label

'Input Parameters Label
Me.InputLabel.Location = New System.Drawing.Point(5, 20)
Me.InputLabel.AutoSize = True
Me.InputLabel.Font = New Font("Tahoma", 12)
Me.InputLabel.Text = "Input Parameters"

'Input; Alloy Type Label
Me.AlloyLabel.Location = New System.Drawing.Point(5, 50)
Me.AlloyLabel.AutoSize = True
Me.AlloyLabel.Font = New Font("Tahoma", 10)
Me.AlloyLabel.Text = "Alloy Type"

'Input; Alloy List
Me.AAlloyList.Location = New System.Drawing.Point(5, 70)
Me.AAlloyList.Items.Add("5083")
Me.AAlloyList.Items.Add("5456")
Me.AAlloyList.Items.Add("Other Alloy")
Me.AAlloyListEnable = False

'Input; Contast Temp Selection
```

```
Me.ACTempBox.Location = New System.Drawing.Point(5, 110)
Me.ACTempBox.AutoSize = True
ACTempBoxEnable = False

'Input; Temp Label
Me.TempLabel.Location = New System.Drawing.Point(25, 110)
Me.TempLabel.AutoSize = True
Me.TempLabel.Font = New Font("Tahoma", 10)
Me.TempLabel.Text = "Constant Temperature Profile"

'Input; Contast Temp
Me.ACTempText.Location = New System.Drawing.Point(25, 130)
Me.ACTempText.Size = New System.Drawing.Point(60, 20)
Me.ACTempText.Enabled = False
ACTempEnable = False

'Input; Contast Temp Unit Label
Me.ACTempUnitLabel.Location = New System.Drawing.Point(85, 132)
Me.ACTempUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ACTempUnitLabel.Font = New Font("Tahoma", 8)
Me.ACTempUnitLabel.Text = "F"

'Input; Cyclic Temp Selection
Me.ACycTempBox.Location = New System.Drawing.Point(5, 170)
Me.ACycTempBox.AutoSize = True
ACycTempBoxEnable = False

'Input; Cyclic Temp Label
Me.ACycTempLabel.Location = New System.Drawing.Point(25, 170)
Me.ACycTempLabel.AutoSize = True
Me.ACycTempLabel.Font = New Font("Tahoma", 10)
Me.ACycTempLabel.Text = "Cyclic Temperature Profile"

'Input; Cyclic Winter Temp Label
Me.AWinTempLabel.Location = New System.Drawing.Point(25, 190)
Me.AWinTempLabel.AutoSize = True
Me.AWinTempLabel.Font = New Font("Tahoma", 8)
Me.AWinTempLabel.Text = "Max Winter Temperature on Exposed Surface"

'Input; Cyclic Winter Temp Text
Me.AWinTempText.Location = New System.Drawing.Point(25, 210)
Me.AWinTempText.Size = New System.Drawing.Point(60, 20)
Me.AWinTempText.Enabled = False
AWinTempEnable = False
```

```
'Input; Cyclic Winter Temp Unit Label
Me.AWinTempUnitLabel.Location = New System.Drawing.Point(85, 212)
Me.AWinTempUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.AWinTempUnitLabel.Font = New Font("Tahoma", 8)
Me.AWinTempUnitLabel.Text = "F"

'Input; Cyclic Spring Temp Label
Me.ASprTempLabel.Location = New System.Drawing.Point(25, 240)
Me.ASprTempLabel.AutoSize = True
Me.ASprTempLabel.Font = New Font("Tahoma", 8)
Me.ASprTempLabel.Text = "Max Spring Temperature on Exposed Surface"

'Input; Cyclic Spring Temp Text
Me.ASprTempText.Location = New System.Drawing.Point(25, 260)
Me.ASprTempText.Size = New System.Drawing.Point(60, 20)
Me.ASprTempText.Enabled = False
ASprTempEnable = False

'Input; Cyclic Spring Temp Unit Label
Me.ASprTempUnitLabel.Location = New System.Drawing.Point(85, 262)
Me.ASprTempUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ASprTempUnitLabel.Font = New Font("Tahoma", 8)
Me.ASprTempUnitLabel.Text = "F"

'Input; Cyclic Summer Temp Label
Me.ASumTempLabel.Location = New System.Drawing.Point(25, 290)
Me.ASumTempLabel.AutoSize = True
Me.ASumTempLabel.Font = New Font("Tahoma", 8)
Me.ASumTempLabel.Text = "Max Summer Temperature on Exposed Surface"

'Input; Cyclic Summer Temp Text
Me.ASumTempText.Location = New System.Drawing.Point(25, 310)
Me.ASumTempText.Size = New System.Drawing.Point(60, 20)
Me.ASumTempText.Enabled = False
ASumTempEnable = False

'Input; Cyclic Summer Temp Unit Label
Me.ASumTempUnitLabel.Location = New System.Drawing.Point(85, 312)
Me.ASumTempUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ASumTempUnitLabel.Font = New Font("Tahoma", 8)
Me.ASumTempUnitLabel.Text = "F"

'Input; Cyclic Fall Temp Label
Me.AFalTempLabel.Location = New System.Drawing.Point(25, 340)
Me.AFalTempLabel.AutoSize = True
```

```
Me.AFalTempLabel.Font = New Font("Tahoma", 8)
Me.AFalTempLabel.Text = "Max Fall Temperature on Exposed Surface"

'Input; Cyclic Fall Temp Text
Me.AFalTempText.Location = New System.Drawing.Point(25, 360)
Me.AFalTempText.Size = New System.Drawing.Point(60, 20)
Me.AFalTempText.Enabled = False
AFalTempEnable = False

'Input; Cyclic Fall Temp Unit Label
Me.AFalTempUnitLabel.Location = New System.Drawing.Point(85, 362)
Me.AFalTempUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.AFalTempUnitLabel.Font = New Font("Tahoma", 8)
Me.AFalTempUnitLabel.Text = "F"

'Input; Bulk Magnesium Concentration Label
Me.ABulkConcLabel.Location = New System.Drawing.Point(5, 400)
Me.ABulkConcLabel.AutoSize = True
Me.ABulkConcLabel.Font = New Font("Tahoma", 10)
Me.ABulkConcLabel.Text = "Bulk Mg Concentration"

'Input; Bulk Magnesium Concentration Text
Me.ABulkConcText.Location = New System.Drawing.Point(5, 420)
Me.ABulkConcText.Size = New System.Drawing.Point(60, 20)
ABulkConcEnable = False

'Input; Bulk Magnesium Concentration Unit Label
Me.ABulkConcUnitLabel = New System.Windows.Forms.Label
Me.ABulkConcUnitLabel.Location = New System.Drawing.Point(65, 420)
Me.ABulkConcUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ABulkConcUnitLabel.Font = New Font("Tahoma", 10)
Me.ABulkConcUnitLabel.Text = "weight %"

'Input; Advanced Parameters Selection
Me.AAdvancedBox.Location = New System.Drawing.Point(5, 460)
Me.AAdvancedBox.AutoSize = True

'Input; Advanced Parameters Selection Label
Me.AAdvancedLabel.Location = New System.Drawing.Point(25, 460)
Me.AAdvancedLabel.AutoSize = True
Me.AAdvancedLabel.Font = New Font("Tahoma", 10)
Me.AAdvancedLabel.Text = "Advanced Model Parameters"
AAdvancedEnable = False

'Advanced Parameters Separation Line
```

```
Me.ALine.Location = New System.Drawing.Point(5, 480)
Me.ALine.Size = New System.Drawing.Size(655, 1)
Me.ALine.BackColor = Color.Black

'Advanced Parameters Input; Bulk Magnesium Diffusion Label
Me.ABulkDifLabel.Location = New System.Drawing.Point(25, 490)
Me.ABulkDifLabel.AutoSize = True
Me.ABulkDifLabel.Font = New Font("Tahoma", 8)
Me.ABulkDifLabel.Text = "Bulk Mg Diffusion Coefficient"

'Advanced Parameters Input; Bulk Magnesium Diffusion Text
Me.ABulkDifText.Location = New System.Drawing.Point(25, 510)
Me.ABulkDifText.Size = New System.Drawing.Point(60, 20)
Me.ABulkDifText.Enabled = False
Me.ABulkDifText.Text = "1.52"
ABulkDifEnable = True

'Advanced Parameters Input; Bulk Magnesium Diffusion Unit Label
Me.ABulkDifUnitLabel.Location = New System.Drawing.Point(85, 512)
Me.ABulkDifUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ABulkDifUnitLabel.Font = New Font("Tahoma", 8)
Me.ABulkDifUnitLabel.Text = "m2/s"

'Advanced Parameters Input; Grain Boundary Magnesium Diffusion Label
Me.AGBDifLabel.Location = New System.Drawing.Point(25, 540)
Me.AGBDifLabel.AutoSize = True
Me.AGBDifLabel.Font = New Font("Tahoma", 8)
Me.AGBDifLabel.Text = "Grain Boundary Diffusion Coefficient"

'Advanced Parameters Input; Grain Boundary Magnesium Diffusion Text
Me.AGBDifText.Location = New System.Drawing.Point(25, 560)
Me.AGBDifText.Size = New System.Drawing.Point(60, 20)
Me.AGBDifText.Enabled = False
Me.AGBDifText.Text = "1.52"
AGBDifEnable = True

'Advanced Parameters Input; Grain Boundary Magnesium Diffusion Unit Label
Me.AGBDifUnitLabel.Location = New System.Drawing.Point(85, 562)
Me.AGBDifUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.AGBDifUnitLabel.Font = New Font("Tahoma", 8)
Me.AGBDifUnitLabel.Text = "m2/s"

'Advanced Parameters Input; Interface Magnesium Diffusion Label
Me.AIntDifLabel.Location = New System.Drawing.Point(25, 590)
Me.AIntDifLabel.AutoSize = True
```

```
Me.AIntDifLabel.Font = New Font("Tahoma", 8)
Me.AIntDifLabel.Text = "Precipitate Interface Diffusion Coefficient"

'Advanced Parameters Input; Interface Magnesium Diffusion Text
Me.AIntDifText.Location = New System.Drawing.Point(25, 610)
Me.AIntDifText.Size = New System.Drawing.Point(60, 20)
Me.AIntDifText.Enabled = False
Me.AIntDifText.Text = "1.52"
AIntDifEnable = True

'Advanced Parameters Input; Interface Magnesium Diffusion Unit Label
Me.AIntDifUnitLabel.Location = New System.Drawing.Point(85, 612)
Me.AIntDifUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.AIntDifUnitLabel.Font = New Font("Tahoma", 8)
Me.AIntDifUnitLabel.Text = "m2/s"

'Advanced Parameters Input; Nucleation Density Label
Me.NucDenLabel.Location = New System.Drawing.Point(255, 490)
Me.NucDenLabel.AutoSize = True
Me.NucDenLabel.Font = New Font("Tahoma", 8)
Me.NucDenLabel.Text = "Grain Boundary Nucleation Density"

'Advanced Parameters Input; Nucleation Density Text
Me.NucDenText.Location = New System.Drawing.Point(255, 510)
Me.NucDenText.Size = New System.Drawing.Point(60, 20)
Me.NucDenText.Enabled = False
Me.NucDenText.Text = "1.52"
NucDenEnable = True

'Advanced Parameters Input; Nucleation Density Unit Label
Me.NucDenUnitLabel.Location = New System.Drawing.Point(315, 512)
Me.NucDenUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.NucDenUnitLabel.Font = New Font("Tahoma", 8)
Me.NucDenUnitLabel.Text = "Nuclei/cm"

'Advanced Parameters Input; Contact Angle Label
Me.ContAngLabel.Location = New System.Drawing.Point(255, 540)
Me.ContAngLabel.AutoSize = True
Me.ContAngLabel.Font = New Font("Tahoma", 8)
Me.ContAngLabel.Text = "Precipitate Contact Angle"

'Advanced Parameters Input; Contact Angle Text
Me.ContAngText.Location = New System.Drawing.Point(255, 560)
Me.ContAngText.Size = New System.Drawing.Point(60, 20)
Me.ContAngText.Enabled = False
```

```
Me.ContAngText.Text = "1.52"
ContAngEnable = True

'Advanced Parameters Input; Contact Angle Unit Label
Me.ContAngUnitLabel.Location = New System.Drawing.Point(315, 562)
Me.ContAngUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ContAngUnitLabel.Font = New Font("Tahoma", 8)
Me.ContAngUnitLabel.Text = "radians"

'Advanced Parameters Input; Surface Tension Label
Me.SurfTenLabel.Location = New System.Drawing.Point(255, 590)
Me.SurfTenLabel.AutoSize = True
Me.SurfTenLabel.Font = New Font("Tahoma", 8)
Me.SurfTenLabel.Text = "Precipitat Surface Tension"

'Advanced Parameters Input; Surface Tension Text
Me.SurfTenText.Location = New System.Drawing.Point(255, 610)
Me.SurfTenText.Size = New System.Drawing.Point(60, 20)
Me.SurfTenText.Enabled = False
Me.SurfTenText.Text = "1.52"
SurfTenEnable = True

'Advanced Parameters Input; Surface Tension Unit Label
Me.SurfTenUnitLabel.Location = New System.Drawing.Point(315, 612)
Me.SurfTenUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.SurfTenUnitLabel.Font = New Font("Tahoma", 8)
Me.SurfTenUnitLabel.Text = "N/m"

'Advanced Parameters Input; Beta Phase Magnesium Concentration Label
Me.ABetaConcLabel.Location = New System.Drawing.Point(485, 490)
Me.ABetaConcLabel.AutoSize = True
Me.ABetaConcLabel.Font = New Font("Tahoma", 8)
Me.ABetaConcLabel.Text = "Beta Phase Mg Concentration"

'Advanced Parameters Input; Beta Phase Magnesium Concentration Text
Me.ABetaConcText.Location = New System.Drawing.Point(485, 510)
Me.ABetaConcText.Size = New System.Drawing.Point(60, 20)
Me.ABetaConcText.Enabled = False
Me.ABetaConcText.Text = "1.52"
ABetaConcEnable = True

'Advanced Parameters Input; Beta Phase Magnesium Concentration Unit Label
Me.ABetaConcUnitLabel.Location = New System.Drawing.Point(545, 512)
Me.ABetaConcUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.ABetaConcUnitLabel.Font = New Font("Tahoma", 8)
```

```
Me.ABetaConcUnitLabel.Text = "weight %"

'Advanced Parameters Input; Beta Phase Equilibrium Magnesium Concentration Label
Me.AEqConcLabel.Location = New System.Drawing.Point(485, 540)
Me.AEqConcLabel.AutoSize = True
Me.AEqConcLabel.Font = New Font("Tahoma", 8)
Me.AEqConcLabel.Text = "Equilibirum Matrix Mg Concentration"

'Advanced Parameters Input; Beta Phase Equilibrium Magnesium Concentration Text
Me.AEqConcText.Location = New System.Drawing.Point(485, 560)
Me.AEqConcText.Size = New System.Drawing.Point(60, 20)
Me.AEqConcText.Enabled = False
Me.AEqConcText.Text = "1.52"
AEqConcEnable = True

'Advanced Parameters Input; Beta Phase Equilibrium Magnesium Concentration Unit Label
Me.AEqConcUnitLabel.Location = New System.Drawing.Point(545, 562)
Me.AEqConcUnitLabel.Size = New System.Drawing.Point(75, 20)
Me.AEqConcUnitLabel.Font = New Font("Tahoma", 8)
Me.AEqConcUnitLabel.Text = "weight %"

'Advanced Model Run Button
Me.ARunButton.Location = New System.Drawing.Point(575, 420)
Me.ARunButton.Size = New System.Drawing.Size(75, 20)
Me.ARunButton.Enabled = False
Me.ARunButton.Text = "Run"

'Advanced Model Cancel Button
Me.AXButton.Location = New System.Drawing.Point(575, 450)
Me.AXButton.Size = New System.Drawing.Size(75, 20)
Me.AXButton.Text = "Cancel"

'Output Information Label
Me.OutputLabel.Location = New System.Drawing.Point(285, 20)
Me.OutputLabel.AutoSize = True
Me.OutputLabel.Font = New Font("Tahoma", 12)
Me.OutputLabel.Text = "Output Information"

'Output; Sensitization Time Label
Me.SensitizedTimeLabel.Location = New System.Drawing.Point(285, 50)
Me.SensitizedTimeLabel.Size = New System.Drawing.Size(225, 40)
Me.SensitizedTimeLabel.Font = New Font("Tahoma", 10)
```

```
    Me.SensitizedTimeLabel.Text = "Estimated Time to Threshold Sensitization (25
mg/cm2)"

    'Output; Sensitization Time Text
    Me.SensitizedTimeText.Location = New System.Drawing.Point(285, 90)
    Me.SensitizedTimeText.Size = New System.Drawing.Point(65, 20)
    Me.SensitizedTimeText.Enabled = False
    Me.SensitizedTimeText.Font = New Font("Tahoma", 8, FontStyle.Bold)

    'Output; Sensitization Time Unit Label
    Me.SenTimeUnitLabel.Location = New System.Drawing.Point(350, 90)
    Me.SenTimeUnitLabel.Size = New System.Drawing.Point(60, 20)
    Me.SenTimeUnitLabel.Font = New Font("Tahoma", 10)
    Me.SenTimeUnitLabel.Text = "Years"

    'Output; High Sensitization Time Label
    Me.FailureTimeLabel.Location = New System.Drawing.Point(285, 130)
    Me.FailureTimeLabel.Size = New System.Drawing.Size(225, 40)
    Me.FailureTimeLabel.Font = New Font("Tahoma", 10)
    Me.FailureTimeLabel.Text = "Estimated Time to High Sensitization (40
mg/cm2)"

    'Output; High Sensitization Time Text
    Me.FailureTimeText.Location = New System.Drawing.Point(285, 170)
    Me.FailureTimeText.Size = New System.Drawing.Point(65, 20)
    Me.FailureTimeText.Enabled = False
    Me.FailureTimeText.Font = New Font("Tahoma", 8, FontStyle.Bold)

    'Output; High Sensitization Time Unit Label
    Me.FailTimeUnitLabel.Location = New System.Drawing.Point(350, 170)
    Me.FailTimeUnitLabel.Size = New System.Drawing.Point(60, 20)
    Me.FailTimeUnitLabel.Font = New Font("Tahoma", 10)
    Me.FailTimeUnitLabel.Text = "Years"

    'Adds all relevant components to the Advanced Model Form
    AForm.AutoSize = True
    AForm.Text = "Advanced Sensitization Model Prediction"
    AForm.Controls.Add(Me.InputLabel)
    AForm.Controls.Add(Me.AlloyLabel)
    AForm.Controls.Add(Me.AAlloyList)
    AForm.Controls.Add(Me.ACTempBox)
    AForm.Controls.Add(Me.TempLabel)
    AForm.Controls.Add(Me.ACTempText)
    AForm.Controls.Add(Me.ACTempUnitLabel)
    AForm.Controls.Add(Me.ACycTempBox)
```

```
AForm.Controls.Add(Me.ACycTempLabel)
AForm.Controls.Add(Me.AWinTempLabel)
AForm.Controls.Add(Me.AWinTempText)
AForm.Controls.Add(Me.AWinTempUnitLabel)
AForm.Controls.Add(Me.ASprTempLabel)
AForm.Controls.Add(Me.ASprTempText)
AForm.Controls.Add(Me.ASprTempUnitLabel)
AForm.Controls.Add(Me.ASumTempLabel)
AForm.Controls.Add(Me.ASumTempText)
AForm.Controls.Add(Me.ASumTempUnitLabel)
AForm.Controls.Add(Me.AFalTempLabel)
AForm.Controls.Add(Me.AFalTempText)
AForm.Controls.Add(Me.AFalTempUnitLabel)
AForm.Controls.Add(Me.ABulkConcLabel)
AForm.Controls.Add(Me.ABulkConcText)
AForm.Controls.Add(Me.ABulkConcUnitLabel)
AForm.Controls.Add(Me.AAdvancedBox)
AForm.Controls.Add(Me.AAdvancedLabel)
AForm.Controls.Add(Me.ALine)
AForm.Controls.Add(Me.ABulkDifLabel)
AForm.Controls.Add(Me.ABulkDifText)
AForm.Controls.Add(Me.ABulkDifUnitLabel)
AForm.Controls.Add(Me.AGBDifLabel)
AForm.Controls.Add(Me.AGBDifText)
AForm.Controls.Add(Me.AGBDifUnitLabel)
AForm.Controls.Add(Me.AIntDifLabel)
AForm.Controls.Add(Me.AIntDifText)
AForm.Controls.Add(Me.AIntDifUnitLabel)
AForm.Controls.Add(Me.NucDenLabel)
AForm.Controls.Add(Me.NucDenText)
AForm.Controls.Add(Me.NucDenUnitLabel)
AForm.Controls.Add(Me.ContAngLabel)
AForm.Controls.Add(Me.ContAngText)
AForm.Controls.Add(Me.ContAngUnitLabel)
AForm.Controls.Add(Me.SurfTenLabel)
AForm.Controls.Add(Me.SurfTenText)
AForm.Controls.Add(Me.SurfTenUnitLabel)
AForm.Controls.Add(Me.ABetaConcLabel)
AForm.Controls.Add(Me.ABetaConcText)
AForm.Controls.Add(Me.ABetaConcUnitLabel)
AForm.Controls.Add(Me.AEqConcLabel)
AForm.Controls.Add(Me.AEqConcText)
AForm.Controls.Add(Me.AEqConcUnitLabel)
AForm.Controls.Add(Me.ARunButton)
AForm.Controls.Add(Me.AXButton)
```

```
        AForm.Controls.Add(Me.OutputLabel)
        AForm.Controls.Add(Me.SensitizedTimeLabel)
        AForm.Controls.Add(Me.SensitizedTimeText)
        AForm.Controls.Add(Me.SenTimeUnitLabel)
        AForm.Controls.Add(Me.FailureTimeLabel)
        AForm.Controls.Add(Me.FailureTimeText)
        AForm.Controls.Add(Me.FailTimeUnitLabel)
        AForm.Show()

    End Sub

    ' Ensure Advanced Model Alloy Selection
    Private Sub AAlloyList_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AAlloyList.SelectedIndexChanged

        If 0 <= AAlloyList.SelectedIndex <= 3 Then
            AAlloyListEnable = True
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
             AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True
And ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True
And AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
             ASprTempEnable = True And ASumTempEnable = True And
AFalTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
             AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True
And ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True
And AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub
```

```
' Advanced Model Select Constant Temperature
Private Sub ACTempBox_Enable(ByVal sender As Object, ByVal e As
      System.EventArgs) Handles ACTempBox.CheckStateChanged

   If ACTempBox.Checked = True And ACycTempBoxEnable = False Then
      ACTempText.Enabled = True
      ACTempBoxEnable = True
   ElseIf ACTempBox.Checked = True And ACycTempBoxEnable = True Then
      ACycTempBox.Checked = False
      AWinTempText.Text = ""
      ASprTempText.Text = ""
      ASumTempText.Text = ""
      AFalTempText.Text = ""
      ACTempText.Enabled = True
      ACTempBoxEnable = True
      ACycTempBoxEnable = False
      ARunButton.Enabled = False
   ElseIf ACTempBox.Checked = False Then
      ACTempText.Enabled = False
      ACTempText.Text = ""
      ACTempBoxEnable = False
      ACTempEnable = False
      ARunButton.Enabled = False
   End If

End Sub

' Ensure Advanced Model Constant Temperature Input
Private Sub ACTempText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ACTempText.TextChanged

   If String.IsNullOrEmpty(ACTempText.Text) = True Then
      ARunButton.Enabled = False
      ACTempEnable = False
   ElseIf Double.TryParse(ACTempText.Text, 1) Then
      ACTempEnable = True
   Else
      ARunButton.Enabled = False
      ACTempEnable = False
   End If

   If AAlloyListEnable = True And ABulkConcEnable = True Then
      If ACTempBox.Checked = True And ACTempEnable = True Then
         If AAdvancedBox.Checked = True And ABulkDifEnable = True And
      AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True
```

```
And ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True
And AEqConcEnable = True Then
                ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
                ARunButton.Enabled = True
            End If
         ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
          ASprTempEnable = True And ASumTempEnable = True And
AFalTempEnable = True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
          AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True
And ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True
And AEqConcEnable = True Then
                ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
                ARunButton.Enabled = True
            End If
         End If
      End If

   End Sub

   ' Advanced Model Select Cyclic Temperature
   Private Sub ACycTempBox_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ACycTempBox.CheckStateChanged

      If ACycTempBox.Checked = True And ACTempBoxEnable = False Then
         AWinTempText.Enabled = True
         ASprTempText.Enabled = True
         ASumTempText.Enabled = True
         AFalTempText.Enabled = True
         ACycTempBoxEnable = True
      ElseIf ACycTempBox.Checked = True And ACTempBoxEnable = True Then
         ACTempText.Text = ""
         ACTempBox.Checked = False
         AWinTempText.Enabled = True
         ASprTempText.Enabled = True
         ASumTempText.Enabled = True
         AFalTempText.Enabled = True
         ACycTempBoxEnable = True
         ARunButton.Enabled = False
      ElseIf ACycTempBox.Checked = False Then
         AWinTempText.Enabled = False
         ASprTempText.Enabled = False
         ASumTempText.Enabled = False
```

```
            AFalTempText.Enabled = False
            AWinTempText.Text = ""
            ASprTempText.Text = ""
            ASumTempText.Text = ""
            AFalTempText.Text = ""
            ACycTempBoxEnable = False
            ARunButton.Enabled = False
        End If

    End Sub

    ' Ensure Advanced Model Cyclic Winter Temperature Input
    Private Sub AWinTempText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AWinTempText.TextChanged

        If String.IsNullOrEmpty(AWinTempText.Text) = True Then
            ARunButton.Enabled = False
            AWinTempEnable = False
        ElseIf Double.TryParse(AWinTempText.Text, 1) Then
            AWinTempEnable = True
        Else
            ARunButton.Enabled = False
            AWinTempEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
             ASprTempEnable = True And ASumTempEnable = True And
AFalTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
```

```
        End If
      End If
    End If

  End Sub

  ' Ensure Advanced Model Cyclic Spring Temperature Input
  Private Sub ASprTempText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ASprTempText.TextChanged

    If String.IsNullOrEmpty(ASprTempText.Text) = True Then
      ARunButton.Enabled = False
      ASprTempEnable = False
    ElseIf Double.TryParse(ASprTempText.Text, 1) Then
      ASprTempEnable = True
    Else
      ARunButton.Enabled = False
      ASprTempEnable = False
    End If

    If AAlloyListEnable = True And ABulkConcEnable = True Then
      If ACTempBox.Checked = True And ACTempEnable = True Then
        If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
          ARunButton.Enabled = True
        ElseIf AAdvancedBox.Checked = False Then
          ARunButton.Enabled = True
        End If
      ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
        If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
          ARunButton.Enabled = True
        ElseIf AAdvancedBox.Checked = False Then
          ARunButton.Enabled = True
        End If
      End If
    End If

  End Sub
```

```
    ' Ensure Advanced Model Cyclic Summer Temperature Input
    Private Sub ASumTempText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ASumTempText.TextChanged

        If String.IsNullOrEmpty(ASumTempText.Text) = True Then
            ARunButton.Enabled = False
            ASumTempEnable = False
        ElseIf Double.TryParse(ASumTempText.Text, 1) Then
            ASumTempEnable = True
        Else
            ARunButton.Enabled = False
            ASumTempEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub

    ' Ensure Advanced Model Cyclic Fall Temperature Input
    Private Sub AFalTempText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AFalTempText.TextChanged
```

```
        If String.IsNullOrEmpty(AFalTempText.Text) = True Then
            ARunButton.Enabled = False
            AFalTempEnable = False
        ElseIf Double.TryParse(AFalTempText.Text, 1) Then
            AFalTempEnable = True
        Else
            ARunButton.Enabled = False
            AFalTempEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub

    ' Ensure Advanced Model Bulk Magnesium Concentration Entered
    Private Sub ABulkConc_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ABulkConcText.TextChanged

        If String.IsNullOrEmpty(ABulkConcText.Text) = True Then
            ARunButton.Enabled = False
            ABulkConcEnable = False
        ElseIf Double.TryParse(ABulkConcText.Text, 1) Then
            ABulkConcEnable = True
```

```
        Else
            ARunButton.Enabled = False
            ABulkConcEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub

    ' Advanced Model Select Advanced Parameters
    Private Sub AAdvancedBox_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AAdvancedBox.CheckStateChanged

        If AAdvancedBox.Checked = True And AAdvancedEnable = False Then
            ABulkDifText.Enabled = True
            AGBDifText.Enabled = True
            AIntDifText.Enabled = True
            NucDenText.Enabled = True
            ContAngText.Enabled = True
            SurfTenText.Enabled = True
            ABetaConcText.Enabled = True
            AEqConcText.Enabled = True
```

```
        ElseIf AAdvancedBox.Checked = False Then
            ABulkDifText.Enabled = False
            AGBDifText.Enabled = False
            AIntDifText.Enabled = False
            NucDenText.Enabled = False
            ContAngText.Enabled = False
            SurfTenText.Enabled = False
            ABetaConcText.Enabled = False
            AEqConcText.Enabled = False
            ABulkDifText.Text = 1.52
            AGBDifText.Text = 1.52
            AIntDifText.Text = 1.52
            NucDenText.Text = 1.52
            ContAngText.Text = 1.52
            SurfTenText.Text = 1.52
            ABetaConcText.Text = 1.52
            AEqConcText.Text = 1.52
            AAdvancedEnable = False

        End If

    End Sub

    ' Ensure Advanced Model Bulk Diffusion Input
    Private Sub ABulkDifText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ABulkDifText.TextChanged

        If String.IsNullOrEmpty(ABulkDifText.Text) = True Then
            ARunButton.Enabled = False
            ABulkDifEnable = False
        ElseIf Double.TryParse(ABulkDifText.Text, 1) Then
            ABulkDifEnable = True
        Else
            ARunButton.Enabled = False
            ABulkDifEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
```

```
                ARunButton.Enabled = True
            End If
        ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
                ARunButton.Enabled = True
            End If
        End If
    End If

  End Sub

  ' Ensure Advanced Model Grain Boundary Diffusion Input
  Private Sub AGBDifText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AGBDifText.TextChanged

    If String.IsNullOrEmpty(AGBDifText.Text) = True Then
        ARunButton.Enabled = False
        AGBDifEnable = False
    ElseIf Double.TryParse(AGBDifText.Text, 1) Then
        AGBDifEnable = True
    Else
        ARunButton.Enabled = False
        AGBDifEnable = False
    End If

    If AAlloyListEnable = True And ABulkConcEnable = True Then
        If ACTempBox.Checked = True And ACTempEnable = True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
                ARunButton.Enabled = True
            End If
        ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
```

```
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
              ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
              ARunButton.Enabled = True
            End If
          End If
        End If

    End Sub

    ' Ensure Advanced Model Interface Diffusion Input
    Private Sub AIntDifText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AIntDifText.TextChanged

        If String.IsNullOrEmpty(AIntDifText.Text) = True Then
          ARunButton.Enabled = False
          AIntDifEnable = False
        ElseIf Double.TryParse(AIntDifText.Text, 1) Then
          AIntDifEnable = True
        Else
          ARunButton.Enabled = False
          AIntDifEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
          If ACTempBox.Checked = True And ACTempEnable = True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
              ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
              ARunButton.Enabled = True
            End If
          ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
              ARunButton.Enabled = True
```

```
            ElseIf AAdvancedBox.Checked = False Then
              ARunButton.Enabled = True
            End If
          End If
        End If

    End Sub

    ' Ensure Advanced Model Nucleation Density Input
    Private Sub NucDenText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles NucDenText.TextChanged

        If String.IsNullOrEmpty(NucDenText.Text) = True Then
          ARunButton.Enabled = False
          NucDenEnable = False
        ElseIf Double.TryParse(NucDenText.Text, 1) Then
          NucDenEnable = True
        Else
          ARunButton.Enabled = False
          NucDenEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
          If ACTempBox.Checked = True And ACTempEnable = True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
              ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
              ARunButton.Enabled = True
            End If
          ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
            If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
              ARunButton.Enabled = True
            ElseIf AAdvancedBox.Checked = False Then
              ARunButton.Enabled = True
            End If
          End If
        End If
```

```
    End Sub

    ' Ensure Advanced Model Contact Angle Input
    Private Sub ContAngText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ContAngText.TextChanged

        If String.IsNullOrEmpty(ContAngText.Text) = True Then
            ARunButton.Enabled = False
            ContAngEnable = False
        ElseIf Double.TryParse(ContAngText.Text, 1) Then
            ContAngEnable = True
        Else
            ARunButton.Enabled = False
            ContAngEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub

    ' Ensure Advanced Model Surface Tension Input
```

```
    Private Sub SurfTenText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles SurfTenText.TextChanged

        If String.IsNullOrEmpty(SurfTenText.Text) = True Then
            ARunButton.Enabled = False
            SurfTenEnable = False
        ElseIf Double.TryParse(SurfTenText.Text, 1) Then
            SurfTenEnable = True
        Else
            ARunButton.Enabled = False
            SurfTenEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub

    ' Ensure Advanced Model Beta Phase Magnesium Concentration Input
    Private Sub ABetaConcText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ABetaConcText.TextChanged

        If String.IsNullOrEmpty(ABetaConcText.Text) = True Then
            ARunButton.Enabled = False
```

```
        ABetaConcEnable = False
      ElseIf Double.TryParse(ABetaConcText.Text, 1) Then
        ABetaConcEnable = True
      Else
        ARunButton.Enabled = False
        ABetaConcEnable = False
      End If

      If AAlloyListEnable = True And ABulkConcEnable = True Then
        If ACTempBox.Checked = True And ACTempEnable = True Then
          If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
            ARunButton.Enabled = True
          ElseIf AAdvancedBox.Checked = False Then
            ARunButton.Enabled = True
          End If
        ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
          If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
            ARunButton.Enabled = True
          ElseIf AAdvancedBox.Checked = False Then
            ARunButton.Enabled = True
          End If
        End If
      End If

    End Sub

    ' Ensure Advanced Model Equilibriuim Magnesium Concentration Input
    Private Sub AEqConcText_Enable(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AEqConcText.TextChanged

      If String.IsNullOrEmpty(AEqConcText.Text) = True Then
        ARunButton.Enabled = False
        AEqConcEnable = False
      ElseIf Double.TryParse(AEqConcText.Text, 1) Then
        AEqConcEnable = True
      Else
        ARunButton.Enabled = False
```

```
            AEqConcEnable = False
        End If

        If AAlloyListEnable = True And ABulkConcEnable = True Then
            If ACTempBox.Checked = True And ACTempEnable = True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            ElseIf ACycTempBox.Checked = True And AWinTempEnable = True And
ASprTempEnable = True And ASumTempEnable = True And AFalTempEnable =
True Then
                If AAdvancedBox.Checked = True And ABulkDifEnable = True And
AGBDifEnable = True And AIntDifEnable = True And NucDenEnable = True And
ContAngEnable = True And SurfTenEnable = True And ABetaConcEnable = True And
AEqConcEnable = True Then
                    ARunButton.Enabled = True
                ElseIf AAdvancedBox.Checked = False Then
                    ARunButton.Enabled = True
                End If
            End If
        End If

    End Sub

    ' Advanced Model Run
    Private Sub ARunButton_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles ARunButton.Click

        ' Define all variables
        Dim T As Double ' Temperature
        Dim Ds As Double ' Diffusion Coefficient in the transition layer
        Dim Db As Double ' Diffusion Coefficient in the beta phase
        Dim Gamma As Double ' Surface Tension
        Dim Phi As Double 'Precipitate Contact Angle
        Dim Omega As Double ' Molar Volume
        Dim Epsilon As Double ' Transition layer thickness
        Dim Na As Double ' Concentration in matrix
        Dim Nb As Double ' Concentration in beta phase
        Dim Nab As Double ' Equilibrium concentration
        Dim Ns As Double
```

```
Dim Dm As Double ' Diffusion Coefficient in the matrix
Dim x0 As Double ' Beta phase radius
Dim w0 As Double ' Time steps
Dim Lambda As Double ' Unit Length
Dim t0 As Double
Dim Ra0 As Double
Dim tz As Double
Dim Jm As Double
Dim Rsu As Double
Dim Cosga As Double
Dim V0 As Double
Dim Gw0 As Double
Dim time As Double
Dim Ra As Double ' Length of beta phase / 2
Dim w As Double
Dim dx As Double
Dim dV As Double
Dim V1 As Double
Dim Gw1 As Double
Dim x1 As Double
Dim SS As Double
Dim lef As Double
Dim L As Double
Dim BetaTheta As Double ' Continuity of beta phase
Dim SensitizedTime As Double
Dim SensitizedCheck = True
Dim FailureTime As Double
Dim GRate As Double ' Reaction rate of the Grain Boundary
Dim BRate As Double ' Reaction rate of the beta phase
Dim PRate As Double ' Reaction rate of pre beta phase
Dim PreBetaFraction As Double ' "Pre Beta" fraction of continious beta phase
Dim MLThetaCutoff As Double ' Continuity cutoff for model transition
Dim ML As Double ' Predicted Mass Loss
Dim i = 1

If FTempList.SelectedIndex = 0 Then
  T = 343
ElseIf FTempList.SelectedIndex = 1 Then
  T = 333
ElseIf FTempList.SelectedIndex = 2 Then
  T = 323
ElseIf FTempList.SelectedIndex = 3 Then
  T = 313
End If
```

```
    Ds = (0.000045) * Exp(-104200 / (8.314 * T))
    Db = (0.000065) * Exp(-111500 / (8.314 * T))
    Gamma = 0.3
    Phi = 18.5 / 180 * PI
    Omega = 0.00001
    Epsilon = 0.0000000005
    Na = 5480.0
    Nb = 40000.0
    Nab = 3250.0
    Ns = (Nb + Nab) / 2
    Dm = (0.0000149) * Exp(-113000 / (8.314 * T))
    Lambda = 0.000000000001
    t0 = PI ^ (1 / 3) * Lambda ^ 2 / (Dm * Db * Db) ^ (1 / 3) * (Nb - Nab) ^ (2 / 3) /
(Na - Nab) ^ (2 / 3)
    x0 = 0.5
    w0 = 0.5

    tz = w0 * t0

    Ra = x0 * Lambda

    GRate = 5 / (86400 * 0.5 * 2700)
    BRate = 45 / (86400 * 0.5 * 2700)
    PRate = (GRate + 2 * BRate) / 3
    PreBetaFraction = 0.13
    MLThetaCutoff = 1 / (1 + 2 * PreBetaFraction)
    Cosga = Cos(Phi) / Rsu
    V0 = Tan(Phi) / (1 - 1 / (1 + Cosga) ^ 2)
    Gw0 = w0 ^ 0.5
    Ra0 = x0 * Lambda
    time = tz + 2 * t0
    Jm = (Na - Nab) * Dm ^ 0.5 / (PI * tz) ^ 0.5
    Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 * (4 * PI *
Db * tz - PI * Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5

    'First Stage

    Do Until i = 100000000
      If 40 < ML Then
        Exit Do
      End If

      If 25 < ML And SensitizedCheck = True Then
        SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 1)
        SensitizedCheck = False
```

```
        End If

        w = w0 + 2 '%the number "1" in this line actually is the time step
        Ra = x0 * Lambda
        time = w * t0
        Jm = (Na - Nab) * Dm ^ 0.5 / (PI * time) ^ 0.5
        Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (4 * PI *
Db * T - PI * Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
        Cosga = Cos(Phi) / Rsu
        V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
        dV = (V1 - V0) / 1
        dx = 4 * Gw0 / x0 ^ 2 / V0 - x0 / 3 / V0 * dV
        x1 = dx * 1 + x0

        Gw1 = time ^ 0.5
        V0 = V1
        x0 = x1
        Gw0 = Gw1
        w0 = w
        SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
        L = 2 * (Db * time) ^ 0.5
        If L >= (0.00000011283) Then
          Exit Do
        End If

        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
          ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
          ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
* 0.5 * 2700
        End If

        i = i + 1

      Loop

      Dim CHD = Ra / 0.00000000000002

      'Second stage

      Dim A = 0.00000000000004
```

```
Dim Ds2 = (0.000045) * Exp(-104200 / (8.314 * T)) '%diffusion coefficient in transition layer
Dim Db2 = (0.000065) * Exp(-111500 / (8.314 * T)) '%(0.65e-4)*exp(-110500/(R*T))
Dim Dm2 = (0.0000149) * Exp(-113000 / (8.314 * T)) ' %125500diffusion coffic0.592ient in matrix
Lambda = 0.00000000000002 '% unit length
t0 = PI ^ 3 * Lambda ^ 2 / Dm2 * (Nb - Nab) ^ 2 / (Na - Nab) ^ 2
Dim CHT = time / t0
x0 = CHD '%Radius of precipitate
w0 = CHT '%Steps of time
Ra0 = x0 * Lambda
tz = w0 * t0
Jm = (Na - Nab) * Dm2 ^ 0.5 / (PI * tz) ^ 0.5
Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds2 * Ns * Gamma * Omega) * Ra0 ^ 2 * (A - PI * Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
Cosga = Cos(Phi) / Rsu
V0 = Tan(Phi) / (1 - 1 / (1 + Cosga) ^ 2)
Gw0 = A / (Lambda ^ 2) / (w0 ^ 0.5)
time = tz + 2 * t0
Ra = x0 * Lambda
i = 0

Do While (i < 2200000000)
  If 40 < ML Then
    Exit Do
  End If

  If 25 < ML And SensitizedCheck = True Then
    SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 1)
    SensitizedCheck = False
  End If

  w = w0 + 2
  Ra = x0 * Lambda
  time = w * t0
  Jm = (Na - Nab) * Dm2 ^ 0.5 / (PI * time) ^ 0.5
  Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds2 * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI * Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
  Cosga = Cos(Phi) / Rsu
  V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
  dV = (V1 - V0) / 1
  dx = Gw0 / x0 ^ 2 / V0 - x0 / 3 / V0 * dV
  x1 = dx * 1 + x0
  Gw1 = A / (Lambda ^ 2) / (w ^ 0.5)
```

```
        V0 = V1
        x0 = x1
        Gw0 = Gw1
        w0 = w
        i = i + 1
        SS = Tan(Phi) * Cosga / (1 + Cosga) * Ra
        lef = time / 1296000

        If lef >= 40 Then
          Exit Do
        End If

        BetaTheta = Ra / (1 * 10 ^ -7)

        If BetaTheta < MLThetaCutoff Then
          ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
        Else
          ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
* 0.5 * 2700
        End If

    Loop

    'Third stage
    Dim h = 0.000001 '%grain size of Al (average)
    Lambda = 0.00000000002 '% unit length (step length)
    t0 = PI * h * Lambda ^ 3 / Dm / A * (Nb - Nab) / (Na - Nab) '%time step(step
length of time)
    x0 = Ra / Lambda '%Radius of precipitate
    w0 = time / t0 '%Steps of time
    Ra0 = x0 * Lambda '%Initial value of length, should be the end of value of last
stage
    tz = w0 * t0 '% Initial value of time, should be the same as the end value of last
stage
    Dim ni = 0
    Dim Sumni = 0
    Dim ani As Double

    Do While ni < 50
        ani = Exp(-((2 * ni + 1) * PI / h) ^ 2 * Dm * tz)
        Sumni = Sumni + ani
        ni = ni + 1
    Loop
```

```
    Dim Jm0 = 4 * (Na - Nab) * Dm / h * Sumni 'the aim of the above few lines is to
calculate the solute flux of Mg to the grain boundary
    Dim Rsu0 = (((4 + 3 * Jm0 * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra0 ^ 2 *
(A - PI * Ra0 ^ 2) / (2 * PI * Ra0 * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
    Cosga = Cos(Phi) / Rsu0
    V0 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
    Dim j = 0
    Dim Sum0 = 0
    Gw0 = Sumni
    i = 0
    Dim ict3 = 16

    Dim nj As Double
    Dim Sumnj As Double
    Dim anj As Double
    Dim RR As Double

    Do While i < 300000000.0

      If 40 < ML Then
        Exit Do
      End If

      If 25 < ML And SensitizedCheck = True Then
        SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 1)
        SensitizedCheck = False
      End If

      w = w0 + 2
      Ra = x0 * Lambda
      time = w * t0
      nj = 0
      Sumnj = 0

      Do While nj < 50
        anj = Exp(-((2 * nj + 1) * PI / h) ^ 2 * Dm * T)
        Sumnj = Sumnj + anj
        nj = nj + 1
      Loop

      Jm = 4 * (Na - Nab) * Dm / h * Sumnj
      Rsu = (((4 + 3 * Jm * 8.314 * T / (Ds * Ns * Gamma * Omega) * Ra ^ 2 * (A - PI *
Ra ^ 2) / (2 * PI * Ra * Epsilon * Sin(Phi))) ^ 0.5 + 1) / 3) ^ 0.5
      Cosga = Cos(Phi) / Rsu
```

```
            V1 = Tan(Phi) * (1 - 1 / (1 + Cosga) ^ 2)
            dV = (V1 - V0) / 2
            dx = 4 * Gw0 / (x0 ^ 2) / V0 - x0 / 3 / V0 * dV
            x1 = dx * 2 + x0
            Gw1 = Sumnj
            V0 = V1
            x0 = x1
            Gw0 = Gw1
            w0 = w
            i = i + 1
            RR = x0 * Lambda
            SS = Tan(Phi) * Cosga / (1 + Cosga) * x0 * Lambda
            lef = time / 1296000

            If RR > 0.0000001 Then
                Exit Do
            End If
            BetaTheta = Ra / (1 * 10 ^ -7)

            If BetaTheta < MLThetaCutoff Then
                ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700
            Else
                ML = BRate * PRate / ((1 - BetaTheta) * BRate + BetaTheta * PRate) * 86400
* 0.5 * 2700
            End If

        Loop

        SensitizedTimeText.Text = SensitizedTime
        SensitizedTimeText.Refresh()
        FailureTime = Math.Round(time / 3600 / 24 / 30 / 12, 1)
        FailureTimeText.Text = FailureTime
        FailureTimeText.Refresh()

    End Sub

    ' Advanced Model Cancel Button
    Private Sub AXButton_Click(ByVal sender As Object, ByVal e As
System.EventArgs) Handles AXButton.Click

        AForm.Close()
    End Sub
End Class
```

A.2 Main Model Visual Basic Code – User Interface and Selection Operations

```
Sub StandardTempCheck_Change()
  ' This Sub checks for a standard temperature input
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  If Sheets("Model").Shapes("StandardTempCheck").ControlFormat.Value = 1 Then
    Sheets("Model").Shapes("InputTempCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("StandardTempBox").ControlFormat.Enabled = True
    Cells(7, 1).Interior.ColorIndex = 2
    Cells(4, 1).Interior.ColorIndex = 2
    Cells(5, 3).Interior.ColorIndex = 37
    Sheets("Model").Range("D9:D12").Interior.ColorIndex = 2
    Sheets("Model").Range("D9:D12").ClearContents
    Sheets("Model").Range("D9:D12").Locked = True
  ElseIf Sheets("Model").Shapes("StandardTempCheck").ControlFormat.Value = -
4146 Then
    Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value = 0
    Sheets("Model").Shapes("StandardTempBox").ControlFormat.Enabled = False
    Cells(4, 1).Interior.ColorIndex = 37
    Cells(7, 1).Interior.ColorIndex = 37
    Cells(5, 3).Interior.ColorIndex = 2
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub InputTempCheck_Change()
  ' This Sub checks for user inputted temperature information
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  If Sheets("Model").Shapes("InputTempCheck").ControlFormat.Value = 1 Then
```

```
      Sheets("Model").Shapes("StandardTempCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value = 0
      Sheets("Model").Shapes("StandardTempBox").ControlFormat.Enabled = False
      Cells(5, 3).Interior.ColorIndex = 2
      Cells(4, 1).Interior.ColorIndex = 2
      Cells(7, 1).Interior.ColorIndex = 2
      Sheets("Model").Range("D9:D12").Interior.ColorIndex = 37
      Sheets("Model").Range("D9:D12").Locked = False
   ElseIf Sheets("Model").Shapes("InputTempCheck").ControlFormat.Value = -4146
Then
      Cells(4, 1).Interior.ColorIndex = 37
      Cells(7, 1).Interior.ColorIndex = 37
      Sheets("Model").Range("D9:D12").Interior.ColorIndex = 2
      Sheets("Model").Range("D9:D12").ClearContents
      Sheets("Model").Range("D9:D12").Locked = True
   End If
   Sheets("Model").Protect Password:="ald1234"
   Sheets("Data").Protect Password:="ald1234"
End Sub

Sub StandardAlloyCheck_Change()
   ' This Sub checks for a standard alloy input
   Sheets("Model").Unprotect Password:="ald1234"
   Sheets("Data").Unprotect Password:="ald1234"
   Cells(4, 13).Value = ""
   Cells(5, 13).Value = ""
   Sheets("Data").Range("F1:K7").Value = ""
   Sheets("Data").Cells(1, 6).Value = "X-Axis"
   Sheets("Data").Cells(2, 6).Value = "Y-Axis"
   Sheets("Data").Cells(2, 7).Value = "Z-Axis"
   If Sheets("Model").Shapes("StandardAlloyCheck").ControlFormat.Value = 1 Then
      Sheets("Model").Shapes("InputAlloyCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Enabled = True
      Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Enabled = False
      Cells(16, 1).Interior.ColorIndex = 2
      Cells(17, 3).Interior.ColorIndex = 37
      Cells(18, 1).Interior.ColorIndex = 2
      Cells(21, 2).Interior.ColorIndex = 2
      Sheets("Model").Range("D20:D20").Interior.ColorIndex = 2
      Sheets("Model").Range("D23:D28").Interior.ColorIndex = 2
      Sheets("Model").Range("D20:D20").ClearContents
      Sheets("Model").Range("D23:D28").ClearContents
      Sheets("Model").Range("D20:D20").Locked = True
      Sheets("Model").Range("D23:D28").Locked = True
```

```
  ElseIf Sheets("Model").Shapes("StandardAlloyCheck").ControlFormat.Value = -
4146 Then
    Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value = 0
    Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Enabled = False
    Cells(16, 1).Interior.ColorIndex = 37
    Cells(18, 1).Interior.ColorIndex = 37
    Cells(17, 3).Interior.ColorIndex = 2
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub InputAlloyCheck_Change()
  ' This Sub checks for user inputted alloy information
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  If Sheets("Model").Shapes("InputAlloyCheck").ControlFormat.Value = 1 Then
    Sheets("Model").Shapes("StandardAlloyCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value = 0
    Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Enabled = False
    Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Enabled = True
    Cells(16, 1).Interior.ColorIndex = 2
    Cells(18, 1).Interior.ColorIndex = 2
    Cells(17, 3).Interior.ColorIndex = 2
    Cells(21, 2).Interior.ColorIndex = 35
    Sheets("Model").Range("D20:D20").Interior.ColorIndex = 37
    Sheets("Model").Range("D20:D20").Locked = False
  ElseIf Sheets("Model").Shapes("InputAlloyCheck").ControlFormat.Value = -4146
Then
    Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Value = -4146
    Cells(16, 1).Interior.ColorIndex = 37
    Cells(18, 1).Interior.ColorIndex = 37
    Cells(21, 2).Interior.ColorIndex = 2
    Sheets("Model").Range("D20:D20").Interior.ColorIndex = 2
    Sheets("Model").Range("D23:D28").Interior.ColorIndex = 2
    Sheets("Model").Range("D20:D20").ClearContents
    Sheets("Model").Range("D20:D20").Locked = True
  End If
```

```
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub AdvancedCheck_Change()
  ' This Sub checks for user inputted advanced alloy information
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  If Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Value = 1 Then
    Cells(21, 2).Interior.ColorIndex = 2
    Sheets("Model").Range("D23:D28").Interior.ColorIndex = 37
    Sheets("Model").Range("D23:D28").Locked = False
  ElseIf Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Value = -4146
Then
    If Sheets("Model").Shapes("InputAlloyCheck").ControlFormat.Value = 1 Then
      Cells(21, 2).Interior.ColorIndex = 35
    ElseIf Sheets("Model").Shapes("InputAlloyCheck").ControlFormat.Value = -4146
Then
      Cells(21, 2).Interior.ColorIndex = 2
    End If
    Sheets("Model").Range("D23:D28").Interior.ColorIndex = 2
    Sheets("Model").Range("D23:D28").ClearContents
    Sheets("Model").Range("D23:D28").Locked = True
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub TestMassLossCheck_Change()
  ' This Sub checks for user inputted test mass loss information
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  Dim OtherStart As Integer
```

```
  OtherStart = 32
  If Sheets("Model").Shapes("TestMassLossCheck").ControlFormat.Value = 1 Then
    Sheets("Model").Shapes("RemainingTimeCheck").ControlFormat.Value = -4146
    Cells(OtherStart, 1).Interior.ColorIndex = 2
    Cells(OtherStart + 2, 4).Interior.ColorIndex = 37
    Cells(OtherStart + 3, 1).Interior.ColorIndex = 2
    Cells(OtherStart + 5, 4).Interior.ColorIndex = 2
    Cells(OtherStart + 5, 4).Value = ""
    Cells(OtherStart + 2, 4).Locked = False
    Cells(OtherStart + 5, 4).Locked = True
  ElseIf Sheets("Model").Shapes("TestMassLossCheck").ControlFormat.Value = -
4146 Then
    Cells(OtherStart, 1).Interior.ColorIndex = 35
    Cells(OtherStart + 2, 4).Interior.ColorIndex = 2
    Cells(OtherStart + 3, 1).Interior.ColorIndex = 35
    Cells(OtherStart + 5, 4).Interior.ColorIndex = 2
    Cells(OtherStart + 2, 4).Value = ""
    Cells(OtherStart + 2, 4).Locked = True
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub RemainingTimeCheck_Change()
  ' This Sub checks for user inputted in service alloy mass loss information
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  Dim OtherStart As Integer
  OtherStart = 32
  If Sheets("Model").Shapes("RemainingTimeCheck").ControlFormat.Value = 1 Then
    ‘ Sheets("Model").Shapes("TestMassLossCheck").ControlFormat.Value = -4146
    Cells(OtherStart + 3, 1).Interior.ColorIndex = 2
    Cells(OtherStart + 5, 4).Interior.ColorIndex = 37
    Cells(OtherStart, 1).Interior.ColorIndex = 2
    Cells(OtherStart + 2, 4).Interior.ColorIndex = 2
    Cells(OtherStart + 2, 4).Value = ""
    Cells(OtherStart + 5, 4).Locked = False
    Cells(OtherStart + 2, 4).Locked = True
```

```
  ElseIf Sheets("Model").Shapes("RemainingTimeCheck").ControlFormat.Value = -
4146 Then
    Cells(OtherStart + 3, 1).Interior.ColorIndex = 35
    Cells(OtherStart + 5, 4).Interior.ColorIndex = 2
    Cells(OtherStart, 1).Interior.ColorIndex = 35
    Cells(OtherStart + 3, 4).Interior.ColorIndex = 2
    Cells(OtherStart + 5, 4).Value = ""
    Cells(OtherStart + 5, 4).Locked = True
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub GraphCheck_Change()
  ' This Sub checks for user requested graph
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  Dim GraphStart As Integer
  GraphStart = 41
  If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = 1 Then
    Sheets("Model").Shapes("XTimeCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("XTempCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("XGrainCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("YTimeCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("YTempCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("YGrainCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("ZMLCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("ZHighCheck").ControlFormat.Enabled = True
    Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
```

```
    Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
    Cells(GraphStart, 1).Interior.ColorIndex = 2
    Cells(GraphStart + 3, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 4, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 5, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 6, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 8, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 9, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 10, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 11, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 13, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 14, 3).Interior.ColorIndex = 37
    Cells(GraphStart + 15, 3).Interior.ColorIndex = 37
  ElseIf Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
    Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
    Sheets("Model").Shapes("XTimeCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("XTempCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("XGrainCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("YTimeCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("YTempCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("YGrainCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("ZMLCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Enabled = False
    Sheets("Model").Shapes("ZHighCheck").ControlFormat.Enabled = False
    Cells(GraphStart, 1).Interior.ColorIndex = 35
    Cells(GraphStart + 3, 3).Interior.ColorIndex = 2
    Cells(GraphStart + 4, 3).Interior.ColorIndex = 2
    Cells(GraphStart + 5, 3).Interior.ColorIndex = 2
    Cells(GraphStart + 6, 3).Interior.ColorIndex = 2
    Cells(GraphStart + 8, 3).Interior.ColorIndex = 2
    Cells(GraphStart + 9, 3).Interior.ColorIndex = 2
```

```
      Cells(GraphStart + 10, 3).Interior.ColorIndex = 2
      Cells(GraphStart + 11, 3).Interior.ColorIndex = 2
      Cells(GraphStart + 13, 3).Interior.ColorIndex = 2
      Cells(GraphStart + 14, 3).Interior.ColorIndex = 2
      Cells(GraphStart + 15, 3).Interior.ColorIndex = 2
   End If
   Sheets("Model").Protect Password:="ald1234"
   Sheets("Data").Protect Password:="ald1234"
End Sub

Sub XTimeCheck_Change()
   ' This Sub checks for user requested X-Axis of time
   Sheets("Model").Unprotect Password:="ald1234"
   Sheets("Data").Unprotect Password:="ald1234"
   Cells(4, 13).Value = ""
   Cells(5, 13).Value = ""
   Sheets("Data").Range("F1:K7").Value = ""
   Sheets("Data").Cells(1, 6).Value = "X-Axis"
   Sheets("Data").Cells(2, 6).Value = "Y-Axis"
   Sheets("Data").Cells(2, 7).Value = "Z-Axis"
   Dim XStart As Integer
   XStart = 44
   If Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Then
      If Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = 1 Then
         Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
         Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
         Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
         Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
         Cells(XStart, 3).Interior.ColorIndex = 37
         Cells(XStart + 1, 3).Interior.ColorIndex = 37
         Cells(XStart + 2, 3).Interior.ColorIndex = 37
         Cells(XStart + 3, 3).Interior.ColorIndex = 37
         MsgBox ("Selecting Time on the X Axis is incompatable with selecting Time to
Threshold or High Sensitization on the Z Axis.  Please reselect.")
      ElseIf Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Then
         Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
         Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
         Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
         Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
         Cells(XStart, 3).Interior.ColorIndex = 37
         Cells(XStart + 1, 3).Interior.ColorIndex = 37
         Cells(XStart + 2, 3).Interior.ColorIndex = 37
         Cells(XStart + 3, 3).Interior.ColorIndex = 37
```

```
        MsgBox ("Selecting Time on the X Axis is incompatable with selecting Time on
the Y Axis.  Please reselect.")
      Else
        Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
        Cells(XStart, 3).Interior.ColorIndex = 2
        Cells(XStart + 1, 3).Interior.ColorIndex = 2
        Cells(XStart + 2, 3).Interior.ColorIndex = 2
        Cells(XStart + 3, 3).Interior.ColorIndex = 2
      End If
    ElseIf Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146 Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 Then
        MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change X Axis")
        Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1
        Cells(XStart, 3).Interior.ColorIndex = 2
        Cells(XStart + 1, 3).Interior.ColorIndex = 2
        Cells(XStart + 2, 3).Interior.ColorIndex = 2
        Cells(XStart + 3, 3).Interior.ColorIndex = 2
      Else
        Cells(XStart, 3).Interior.ColorIndex = 37
        Cells(XStart + 1, 3).Interior.ColorIndex = 37
        Cells(XStart + 2, 3).Interior.ColorIndex = 37
        Cells(XStart + 3, 3).Interior.ColorIndex = 37
      End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub XTempCheck_Change()
    ' This Sub checks for user requested X-Axis of temperature
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim XStart As Integer
    XStart = 44
    If Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = 1 Then
```

```
      If Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = 1 Then
        Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
        Cells(XStart, 3).Interior.ColorIndex = 37
        Cells(XStart + 1, 3).Interior.ColorIndex = 37
        Cells(XStart + 2, 3).Interior.ColorIndex = 37
        Cells(XStart + 3, 3).Interior.ColorIndex = 37
        MsgBox ("Selecting Temperature on the X Axis is incompatable with selecting
Temperature on the Y Axis.  Please reselect.")
      ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 And
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value <> 1 Then
        MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change the X Axis")
        Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1
        Cells(XStart, 3).Interior.ColorIndex = 2
        Cells(XStart + 1, 3).Interior.ColorIndex = 2
        Cells(XStart + 2, 3).Interior.ColorIndex = 2
        Cells(XStart + 3, 3).Interior.ColorIndex = 2
      Else
        Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
        Cells(XStart, 3).Interior.ColorIndex = 2
        Cells(XStart + 1, 3).Interior.ColorIndex = 2
        Cells(XStart + 2, 3).Interior.ColorIndex = 2
        Cells(XStart + 3, 3).Interior.ColorIndex = 2
      End If
    ElseIf Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146 Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      Else
        Cells(XStart, 3).Interior.ColorIndex = 37
        Cells(XStart + 1, 3).Interior.ColorIndex = 37
        Cells(XStart + 2, 3).Interior.ColorIndex = 37
        Cells(XStart + 3, 3).Interior.ColorIndex = 37
      End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub XMgConcCheck_Change()
    ' This Sub checks for user requested X-Axis of magnesium concentration
```

```
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim XStart As Integer
    XStart = 44
    If Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = 1 Then
        If Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = 1 Then
            Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
            Cells(XStart, 3).Interior.ColorIndex = 37
            Cells(XStart + 1, 3).Interior.ColorIndex = 37
            Cells(XStart + 2, 3).Interior.ColorIndex = 37
            Cells(XStart + 3, 3).Interior.ColorIndex = 37
            MsgBox ("Selecting Magnesium Concentration on the X Axis is incompatable
with selecting Magnesium Concentration on the Y Axis.  Please reselect.")
        ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 And
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value <> 1 Then
            MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change the X Axis")
            Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1
            Cells(XStart, 3).Interior.ColorIndex = 2
            Cells(XStart + 1, 3).Interior.ColorIndex = 2
            Cells(XStart + 2, 3).Interior.ColorIndex = 2
            Cells(XStart + 3, 3).Interior.ColorIndex = 2
        Else
            Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
            Cells(XStart, 3).Interior.ColorIndex = 2
            Cells(XStart + 1, 3).Interior.ColorIndex = 2
            Cells(XStart + 2, 3).Interior.ColorIndex = 2
            Cells(XStart + 3, 3).Interior.ColorIndex = 2
        End If
    ElseIf Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
Then
        If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
        Else
```

```
      Cells(XStart, 3).Interior.ColorIndex = 37
      Cells(XStart + 1, 3).Interior.ColorIndex = 37
      Cells(XStart + 2, 3).Interior.ColorIndex = 37
      Cells(XStart + 3, 3).Interior.ColorIndex = 37
    End If
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub XGrainCheck_Change()
  ' This Sub checks for user requested X-Axis of grain size
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  Dim XStart As Integer
  XStart = 44
  If Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = 1 Then
    If Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = 1 Then
      Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
      Cells(XStart, 3).Interior.ColorIndex = 37
      Cells(XStart + 1, 3).Interior.ColorIndex = 37
      Cells(XStart + 2, 3).Interior.ColorIndex = 37
      Cells(XStart + 3, 3).Interior.ColorIndex = 37
      MsgBox ("Selecting Grain Size on the X Axis is incompatable with selecting
Grain Size on the Y Axis.  Please reselect.")
    ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 And
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value <> 1 Then
      MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change the X Axis")
      Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1
      Cells(XStart, 3).Interior.ColorIndex = 2
      Cells(XStart + 1, 3).Interior.ColorIndex = 2
      Cells(XStart + 2, 3).Interior.ColorIndex = 2
      Cells(XStart + 3, 3).Interior.ColorIndex = 2
    Else
```

```
            Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = -4146
            Cells(XStart, 3).Interior.ColorIndex = 2
            Cells(XStart + 1, 3).Interior.ColorIndex = 2
            Cells(XStart + 2, 3).Interior.ColorIndex = 2
            Cells(XStart + 3, 3).Interior.ColorIndex = 2
        End If
    ElseIf Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = -4146 Then
        If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
        Else
            Cells(XStart, 3).Interior.ColorIndex = 37
            Cells(XStart + 1, 3).Interior.ColorIndex = 37
            Cells(XStart + 2, 3).Interior.ColorIndex = 37
            Cells(XStart + 3, 3).Interior.ColorIndex = 37
        End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub YTimeCheck_Change()
    ' This Sub checks for user requested Y-Axis of time
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim YStart As Integer
    YStart = 49
    If Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Then
        If Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = 1 Then
            Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
            Cells(YStart, 3).Interior.ColorIndex = 37
            Cells(YStart + 1, 3).Interior.ColorIndex = 37
            Cells(YStart + 2, 3).Interior.ColorIndex = 37
            Cells(YStart + 3, 3).Interior.ColorIndex = 37
```

```
        MsgBox ("Selecting Time on the Y Axis is incompatable with selecting Time to
Threshold or High Sensitization on the Z Axis.  Please reselect.")
      ElseIf Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Then
        Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
        Cells(YStart, 3).Interior.ColorIndex = 37
        Cells(YStart + 1, 3).Interior.ColorIndex = 37
        Cells(YStart + 2, 3).Interior.ColorIndex = 37
        Cells(YStart + 3, 3).Interior.ColorIndex = 37
        MsgBox ("Selecting Time on the Y Axis is incompatable with selecting Time on
the X Axis.  Please reselect.")
      Else
        Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
        Cells(YStart, 3).Interior.ColorIndex = 2
        Cells(YStart + 1, 3).Interior.ColorIndex = 2
        Cells(YStart + 2, 3).Interior.ColorIndex = 2
        Cells(YStart + 3, 3).Interior.ColorIndex = 2
      End If
    ElseIf Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146 Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 Then
        MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change the Y Axis")
        Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1
        Cells(YStart, 3).Interior.ColorIndex = 2
        Cells(YStart + 1, 3).Interior.ColorIndex = 2
        Cells(YStart + 2, 3).Interior.ColorIndex = 2
        Cells(YStart + 3, 3).Interior.ColorIndex = 2
      Else
        Cells(YStart, 3).Interior.ColorIndex = 37
        Cells(YStart + 1, 3).Interior.ColorIndex = 37
        Cells(YStart + 2, 3).Interior.ColorIndex = 37
        Cells(YStart + 3, 3).Interior.ColorIndex = 37
      End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub YTempCheck_Change()
    ' This Sub checks for user requested Y-Axis of temperature
```

```
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim YStart As Integer
    YStart = 49
    If Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = 1 Then
        If Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = 1 Then
            Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
            Cells(YStart, 3).Interior.ColorIndex = 37
            Cells(YStart + 1, 3).Interior.ColorIndex = 37
            Cells(YStart + 2, 3).Interior.ColorIndex = 37
            Cells(YStart + 3, 3).Interior.ColorIndex = 37
            MsgBox ("Selecting Temperature on the Y Axis is incompatable with selecting
Temperature on the X Axis.  Please reselect.")
        ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 And
Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value <> 1 Then
            MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change the Y Axis")
            Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1
            Cells(YStart, 3).Interior.ColorIndex = 2
            Cells(YStart + 1, 3).Interior.ColorIndex = 2
            Cells(YStart + 2, 3).Interior.ColorIndex = 2
            Cells(YStart + 3, 3).Interior.ColorIndex = 2
        Else
            Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
            Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
            Cells(YStart, 3).Interior.ColorIndex = 2
            Cells(YStart + 1, 3).Interior.ColorIndex = 2
            Cells(YStart + 2, 3).Interior.ColorIndex = 2
            Cells(YStart + 3, 3).Interior.ColorIndex = 2
        End If
    ElseIf Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146 Then
        If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
        Else
            Cells(YStart, 3).Interior.ColorIndex = 37
```

```
      Cells(YStart + 1, 3).Interior.ColorIndex = 37
      Cells(YStart + 2, 3).Interior.ColorIndex = 37
      Cells(YStart + 3, 3).Interior.ColorIndex = 37
    End If
  End If
  Sheets("Model").Protect Password:="ald1234"
  Sheets("Data").Protect Password:="ald1234"
End Sub

Sub YMgConcCheck_Change()
  ' This Sub checks for user requested Y-Axis of magnesium concetration
  Sheets("Model").Unprotect Password:="ald1234"
  Sheets("Data").Unprotect Password:="ald1234"
  Cells(4, 13).Value = ""
  Cells(5, 13).Value = ""
  Sheets("Data").Range("F1:K7").Value = ""
  Sheets("Data").Cells(1, 6).Value = "X-Axis"
  Sheets("Data").Cells(2, 6).Value = "Y-Axis"
  Sheets("Data").Cells(2, 7).Value = "Z-Axis"
  Dim YStart As Integer
  YStart = 49
  If Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = 1 Then
    If Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = 1 Then
      Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
      Cells(YStart, 3).Interior.ColorIndex = 37
      Cells(YStart + 1, 3).Interior.ColorIndex = 37
      Cells(YStart + 2, 3).Interior.ColorIndex = 37
      Cells(YStart + 3, 3).Interior.ColorIndex = 37
      MsgBox ("Selecting Magnesium Concentration on the Y Axis is incompatable
with selecting Magnesium Concentration on the X Axis.  Please reselect.")
    ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 And
Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value <> 1 Then
      MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change the Y Axis")
      Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
      Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1
      Cells(YStart, 3).Interior.ColorIndex = 2
      Cells(YStart + 1, 3).Interior.ColorIndex = 2
      Cells(YStart + 2, 3).Interior.ColorIndex = 2
      Cells(YStart + 3, 3).Interior.ColorIndex = 2
    Else
      Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
```

```
        Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
        Cells(YStart, 3).Interior.ColorIndex = 2
        Cells(YStart + 1, 3).Interior.ColorIndex = 2
        Cells(YStart + 2, 3).Interior.ColorIndex = 2
        Cells(YStart + 3, 3).Interior.ColorIndex = 2
      End If
    ElseIf Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      Else
        Cells(YStart, 3).Interior.ColorIndex = 37
        Cells(YStart + 1, 3).Interior.ColorIndex = 37
        Cells(YStart + 2, 3).Interior.ColorIndex = 37
        Cells(YStart + 3, 3).Interior.ColorIndex = 37
      End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub YGrainCheck_Change()
    ' This Sub checks for user requested Y-Axis of grain size
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim YStart As Integer
    YStart = 49
    If Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = 1 Then
      If Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = 1 Then
        Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
        Cells(YStart, 3).Interior.ColorIndex = 37
        Cells(YStart + 1, 3).Interior.ColorIndex = 37
        Cells(YStart + 2, 3).Interior.ColorIndex = 37
        Cells(YStart + 3, 3).Interior.ColorIndex = 37
        MsgBox ("Selecting Grain Size on the Y Axis is incompatable with selecting
Grain Size on the X Axis.  Please reselect.")
```

```
      ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 And
Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value <> 1 Then
        MsgBox ("Selecting Mass Loss on the Z Axis requires selecting Time on either
the X or Y Axis.  Please deselect Mass Loss on the Z Axis to change Y Axis")
        Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = 1
        Cells(YStart, 3).Interior.ColorIndex = 2
        Cells(YStart + 1, 3).Interior.ColorIndex = 2
        Cells(YStart + 2, 3).Interior.ColorIndex = 2
        Cells(YStart + 3, 3).Interior.ColorIndex = 2
      Else
        Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = -4146
        Cells(YStart, 3).Interior.ColorIndex = 2
        Cells(YStart + 1, 3).Interior.ColorIndex = 2
        Cells(YStart + 2, 3).Interior.ColorIndex = 2
        Cells(YStart + 3, 3).Interior.ColorIndex = 2
      End If
    ElseIf Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = -4146 Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      Else
        Cells(YStart, 3).Interior.ColorIndex = 37
        Cells(YStart + 1, 3).Interior.ColorIndex = 37
        Cells(YStart + 2, 3).Interior.ColorIndex = 37
        Cells(YStart + 3, 3).Interior.ColorIndex = 37
      End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub ZMLCheck_Change()
    ' This Sub checks for user requested Z-Axis of mass loss
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim ZStart As Integer
    ZStart = 54
    If Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 Then
```

```
      If Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Then
        Cells(ZStart, 3).Interior.ColorIndex = 2
        Cells(ZStart + 1, 3).Interior.ColorIndex = 2
        Cells(ZStart + 2, 3).Interior.ColorIndex = 2
        Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
      ElseIf Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value <> 1 Or
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value <> 1 Then
        Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
        Cells(ZStart, 3).Interior.ColorIndex = 37
        Cells(ZStart + 1, 3).Interior.ColorIndex = 37
        Cells(ZStart + 2, 3).Interior.ColorIndex = 37
        MsgBox ("Time must be selected on either the X or Y Axis in order to select
Mass Loss on the Z Axis.  Please reselect.")
      End If
    ElseIf Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146 Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      Else
        Cells(ZStart, 3).Interior.ColorIndex = 37
        Cells(ZStart + 1, 3).Interior.ColorIndex = 37
        Cells(ZStart + 2, 3).Interior.ColorIndex = 37
      End If
    End If
    Sheets("Model").Protect Password:="ald1234"
    Sheets("Data").Protect Password:="ald1234"
End Sub

Sub ZThresholdCheck_Change()
    ' This Sub checks for user requested Z-Axis of time to threshold sensitization
    Sheets("Model").Unprotect Password:="ald1234"
    Sheets("Data").Unprotect Password:="ald1234"
    Cells(4, 13).Value = ""
    Cells(5, 13).Value = ""
    Sheets("Data").Range("F1:K7").Value = ""
    Sheets("Data").Cells(1, 6).Value = "X-Axis"
    Sheets("Data").Cells(2, 6).Value = "Y-Axis"
    Sheets("Data").Cells(2, 7).Value = "Z-Axis"
    Dim ZStart As Integer
    ZStart = 54
    If Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = 1 Then
      If Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Then
```

```
        Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
        Cells(ZStart, 3).Interior.ColorIndex = 37
        Cells(ZStart + 1, 3).Interior.ColorIndex = 37
        Cells(ZStart + 2, 3).Interior.ColorIndex = 37
        MsgBox ("Selecting Time to Threshold Sensitization on the Z Axis is
incompatable with selecting Time on the X or Y Axis.  Please reselect.")
      Else
        Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
        Cells(ZStart, 3).Interior.ColorIndex = 2
        Cells(ZStart + 1, 3).Interior.ColorIndex = 2
        Cells(ZStart + 2, 3).Interior.ColorIndex = 2
      End If
   ElseIf Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      Else
        Cells(ZStart, 3).Interior.ColorIndex = 37
        Cells(ZStart + 1, 3).Interior.ColorIndex = 37
        Cells(ZStart + 2, 3).Interior.ColorIndex = 37
      End If
   End If
   Sheets("Model").Protect Password:="ald1234"
   Sheets("Data").Protect Password:="ald1234"
End Sub

Sub ZHighCheck_Change()
   ' This Sub checks for user requested Z-Axis of time to high sensitization
   Sheets("Model").Unprotect Password:="ald1234"
   Sheets("Data").Unprotect Password:="ald1234"
   Cells(4, 13).Value = ""
   Cells(5, 13).Value = ""
   Sheets("Data").Range("F1:K7").Value = ""
   Sheets("Data").Cells(1, 6).Value = "X-Axis"
   Sheets("Data").Cells(2, 6).Value = "Y-Axis"
   Sheets("Data").Cells(2, 7).Value = "Z-Axis"
   Dim ZStart As Integer
   ZStart = 54
   If Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = 1 Then
      If Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Then
        Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
```

```
        Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
        Cells(ZStart, 3).Interior.ColorIndex = 37
        Cells(ZStart + 1, 3).Interior.ColorIndex = 37
        Cells(ZStart + 2, 3).Interior.ColorIndex = 37
        MsgBox ("Selecting Time to High Sensitization on the Z Axis is incompatable
with selecting Time on the X or Y Axis.  Please reselect.Axis")
      Else
        Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = -4146
        Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = -4146
        Cells(ZStart, 3).Interior.ColorIndex = 2
        Cells(ZStart + 1, 3).Interior.ColorIndex = 2
        Cells(ZStart + 2, 3).Interior.ColorIndex = 2
      End If
   ElseIf Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = -4146 Then
      If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then
      Else
        Cells(ZStart, 3).Interior.ColorIndex = 37
        Cells(ZStart + 1, 3).Interior.ColorIndex = 37
        Cells(ZStart + 2, 3).Interior.ColorIndex = 37
      End If
   End If
   Sheets("Model").Protect Password:="ald1234"
   Sheets("Data").Protect Password:="ald1234"
End Sub
```

A.3 Main Model Visual Basic Code – Model Mathematics

```
Sub SensitizationPredictiveModel()

   ' Collector Plate Mechanism Based Classical Nucleation Theory of
   ' Intergranular Precipitates as well as capillarity effect controlled
   ' precipitate growth In Al 5xxx Alloy/Nov,10,2014

' Seciton 1 - Variable Callout and Definition
Sheets("Model").Unprotect Password:="ald1234"
Sheets("Data").Unprotect Password:="ald1234"

Dim Pi As Double
Pi = Application.WorksheetFunction.Pi()
Dim T As Double ' Aging temperature
Dim TempA As Double ' Aging temperature fluctuation
Dim Temp0 As Double ' Baseline aging temperature
Dim Temp00 As Double ' Baseline aging temperature 2
```

```
Dim time As Double ' Aging time
Dim Theta As Double ' Contact angle of the precipitates
Dim Gamma As Double ' Interface energy of matrix-precipitate
Dim Omega As Double ' Molar volume
Dim Ca0 As Double ' Baseline Mg concentration within the matrix
Dim Ca As Double ' Mg concentration within the matrix
Dim Cab As Double ' Mg concentration at the matrix-grain boundary interface
Dim Cb As Double ' Mg concentration within beta phase
Dim Cs As Double ' Mg concentration at the matrix-precipitate inteface
Dim Dm As Double  ' Mg diffusion coefficient within Al matrix
Dim DmEa As Double ' Mg diffusion coefficient activation energy within Al matrix
Dim Db As Double ' Mg diffusion coefficient at grain boundary
Dim DbEa As Double ' Mg diffusion coefficient activation energy at grain boundary
Dim Ds As Double  ' Mg diffusion coefficient in transition layer
Dim DsEa As Double ' Mg diffusion coefficient activation energy in transition layer
Dim h As Double ' Grain size
Dim h0 As Double ' Baseline grain size
Dim Delta As Double ' Grain boundary thickness
Dim vat As Double ' Atomic volume of the precipiate
Dim k As Double ' Boltzmann constant
Dim a0 As Double
Dim N0 As Double
Dim Yita As Double
Dim i As Double
Dim dt As Double
Dim R As Double
Dim inc As Integer
Dim N As Double
Dim A As Double
Dim Rc As Double
Dim Jms As Double ' Short term Mg flux to the grain boundary
Dim Jml As Double ' Long term Mg flux to the grain boundary
Dim Js As Double
Dim J As Double ' Mg flux to the grain boundary
Dim ni As Integer
Dim ani As Double
Dim Sumni As Double
Dim Rsu As Double
Dim Cosga As Double
Dim Ri As Double
Dim Kc As Double
Dim CRi As Double
Dim CRx As Double
Dim fPV As Double
Dim BetaTheta As Double ' Continuity of beta phase
```

```
Dim SensitizedTime As Double ' Predicted time to sensitization
Dim SensitizedCheck As Boolean ' Check if sensitization has been reached
Dim FailureTime As Double ' Predicted time to high sensitization
Dim FailureCheck As Boolean ' Check if high sensitization has been reached
Dim ServiceCheck1 As Boolean ' Check if current predicted mass loss is equal to
current sample mass loss
Dim ServiceCheck2 As Boolean ' Check if remaining service life has been requested
Dim ServiceTime As Double 'Current predicted time in service
Dim ServiceML As Double ' Current mass loss result for remaining service prediction
Dim GRate As Double ' Reaction rate of the grain boundary
Dim BRate As Double ' Reaction rate of the beta phase
Dim PRate As Double ' Reaction rate of pre/thin beta phase
Dim PreBetaFraction As Double ' "Pre/Thin" Beta fraction of continious beta phase
Dim MLThetaCutoff As Double ' Continuity cutoff for model transition
Dim ML As Double ' Predicted Mass Loss
Dim ML0 As Double ' Previous Mass Loss
Dim A1 As Double
Dim A2 As Double
Dim Aa As Double
Dim Bb As Double
Dim Dd As Double
Dim e As Double
Dim fPA As Double
Dim Deltag As Double
Dim Rs As Double
Dim DeltaGs As Double
Dim Zed As Double
Dim Betas As Double
Dim Tao0 As Double
Dim Rdta As Double
Dim Vp As Double
Dim Vavl As Double
Dim favl As Double
Dim dNn As Double
Dim dVg
Dim Alpha As Double
Dim dVc As Double
Dim fcoa As Double
Dim dVf As Double
Dim dNc As Double
Dim dVm As Double
Dim dRf As Double
Dim GraphXTimeCheck As Boolean ' Check if graph X-Axis is time
Dim GraphXTempCheck As Boolean ' Check if graph X-Axis is temperature
Dim GraphXGrainCheck As Boolean ' Check if graph X-Axis is nucleation density
```

```
Dim GraphXMgConcCheck As Boolean ' Check if graph X-Axis is magnesium
concentration
Dim GraphYTimeCheck As Boolean ' Check if graph Y-Axis is time
Dim GraphYTempCheck As Boolean ' Check if graph Y-Axis is temperature
Dim GraphYGrainCheck As Boolean ' Check if graph Y-Axis is nucleation density
Dim GraphYMgConcCheck As Boolean ' Check if graph Y-Axis is magnesium
concetration
Dim GraphZMLCheck As Boolean ' Check if graph Z-Axis is mass loss
Dim GraphZThresholdCheck As Boolean ' Check if graph Z-Axis is time to threshold
sensitization
Dim GraphZHighCheck As Boolean ' Check if graph Z-Axis is time to high
sensitization
Dim GraphXLoop As Integer ' Loop counter for multiple data points, X axis
Dim GraphXStart As Integer ' Starting cell for graph X-Axis
Dim GraphYStart As Integer ' Starting cell for graph Y-Axis
Dim GraphTimeLoop As Integer ' Loop counter for multiple time data points
Dim GraphTimeCheck As Boolean ' Check if current value is appropriate data point
Dim GraphYLoop As Integer ' Loop counter for multiple data points, Y axis

ServiceCheck1 = False
ServiceCheck2 = False
GraphXTimeCheck = False
GraphXTempCheck = False
GraphXGrainCheck = False
GraphXMgConcCheck = False
GraphYTimeCheck = False
GraphYTempCheck = False
GraphYGrainCheck = False
GraphYMgConcCheck = False
GraphZMLCheck = False
GraphZThresholdCheck = False
GraphZHighCheck = False
GraphXLoop = 0
GraphYLoop = 0
GraphXStart = 7
GraphYStart = 3
GraphTimeCheck = False

' Check Temperature Input
If Sheets("Model").Shapes("StandardTempCheck").ControlFormat.Value = 1 Then
  If Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value < 1 Then
    MsgBox ("Input Temperature Profile")
    Sheets("Model").Protect
    Sheets("Data").Protect
    Exit Sub
```

```
   ElseIf Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value = 1
Then
       TempA = (71.1 - 48.9) / 2
       Temp0 = 273 + (71.1 + 48.9) / 2
       Temp00 = Temp0
   ElseIf Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value = 2
Then
       TempA = (60 - 46.1) / 2
       Temp0 = 273 + (60 + 46.1) / 2
       Temp00 = Temp0
   ElseIf Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value = 3
Then
       TempA = (46.1 - 40.5) / 2
       Temp0 = 273 + (46.1 + 40.5) / 2
       Temp00 = Temp0
   ElseIf Sheets("Model").Shapes("StandardTempBox").ControlFormat.Value < 3
Then
       MsgBox ("Input Temperature Profile")
       Sheets("Model").Protect
       Sheets("Data").Protect
       Exit Sub
   End If
ElseIf Sheets("Model").Shapes("InputTempCheck").ControlFormat.Value = 1 Then
   If Cells(9, 4).Value = "" Or Cells(10, 4).Value = "" Or Cells(11, 4).Value = "" Or
Cells(12, 4).Value = "" Then
       MsgBox ("Input Temperature Profile")
       Sheets("Model").Protect
       Sheets("Data").Protect
       Exit Sub
   ElseIf IsNumeric(Cells(9, 4).Value) = False Or IsNumeric(Cells(10, 4).Value) =
False Or IsNumeric(Cells(11, 4).Value) = False Or IsNumeric(Cells(12, 4).Value) =
False Then
       MsgBox ("Input Temperature Profile")
       Sheets("Model").Protect
       Sheets("Data").Protect
       Exit Sub
   ElseIf IsNumeric(Cells(9, 4).Value) = True And IsNumeric(Cells(10, 4).Value) =
True And IsNumeric(Cells(11, 4).Value) = True And IsNumeric(Cells(12, 4).Value) =
True Then
       If Cells(9, 4).Value > 210 Or Cells(10, 4).Value > 210 Or Cells(11, 4).Value > 210
Or Cells(12, 4).Value > 210 Or Cells(9, 4).Value < 0 Or Cells(10, 4).Value <     0 Or
Cells(11, 4).Value < 0 Or Cells(12, 4).Value < 0 Then
          MsgBox ("Temperature Input out of Range.  Please check Temperature
Input")
          Sheets("Model").Protect
```

```
        Sheets("Data").Protect
        Exit Sub
      ElseIf Cells(9, 4).Value = Cells(10, 4).Value And Cells(9, 4).Value = Cells(11,
4).Value And Cells(9, 4).Value = Cells(11, 4).Value And Cells(9, 4).Value = Cells(12,
4).Value Then
        TempA = 0
        Temp0 = (Cells(9, 4).Value - 32) * 5 / 9 + 273
        Temp00 = Temp0
      Else
        TempA = (((Cells(9, 4).Value + Cells(10, 4).Value) / 2 + (Cells(11, 4).Value +
Cells(12, 4).Value) / 2) / 2 - 32) * 5 / 9
        Temp0 = (((Cells(9, 4).Value + Cells(10, 4).Value) / 2 + (Cells(11, 4).Value +
Cells(12, 4).Value) / 2) / 2 - 32) * 5 / 9 + 273
        Temp00 = Temp0
      End If
  End If
Else
  MsgBox ("Please select Temperature Input")
  Sheets("Model").Protect
  Sheets("Data").Protect
  Exit Sub
End If

T = Temp0

'Check Alloy Inputs
If Sheets("Model").Shapes("StandardAlloyCheck").ControlFormat.Value = 1 Then
  If Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value < 1 Then
    MsgBox ("Input Alloy")
    Sheets("Model").Protect
    Sheets("Data").Protect
    Exit Sub
  ElseIf Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value = 1
Then
    Ca0 = 0.0485
    DmEa = 114
    DbEa = 112.9
    DsEa = 98
    Theta = 20 / 180 * Pi
    Gamma = 0.068
    h0 = 1.3e-05
  ElseIf Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value = 2
Then
    Ca0 = 0.0485
    DmEa = 117.5
```

```
      DbEa = 112.9
      DsEa = 98
      Theta = 20 / 180 * Pi
      Gamma = 0.068
      h0 = 1.3e-05
   ElseIf Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value = 3
Then
      Ca0 = 0.0485
      DmEa = 115.5
      DbEa = 112.9
      DsEa = 98
      Theta = 20 / 180 * Pi
      Gamma = 0.068
      h0 = 1.3e-05
   ElseIf Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value = 4
Then
      Ca0 = 0.055
      DmEa = 114
      DbEa = 112.9
      DsEa = 95
      Theta = 20 / 180 * Pi
      Gamma = 0.068
      h0 = 1.3e-05
   ElseIf Sheets("Model").Shapes("StandardAlloyBox").ControlFormat.Value < 4
Then
      MsgBox ("Input Alloy")
      Sheets("Model").Protect
      Sheets("Data").Protect
      Exit Sub
   End If
ElseIf Sheets("Model").Shapes("InputAlloyCheck").ControlFormat.Value = 1 Then
   If Cells(20, 4).Value = "" Then
      MsgBox ("Input Alloy Parameters")
      Sheets("Model").Protect
      Sheets("Data").Protect
      Exit Sub
   ElseIf IsNumeric(Cells(20, 4).Value) = False Then
      MsgBox ("Input Alloy Parameters")
      Sheets("Model").Protect
      Sheets("Data").Protect
      Exit Sub
   ElseIf Cells(20, 4).Value < 3 Or Cells(20, 4).Value > 10 Then
      MsgBox ("Alloy Parameters out of Range.  Please check alloy parameter input")
      Sheets("Model").Protect
      Sheets("Data").Protect
```

```
        Exit Sub
    Else
        Ca0 = Cells(20, 4).Value / 100
        DmEa = 114
        DbEa = 112.9
        DsEa = -142.86 * Ca0 + 104.29
        Theta = 20 / 180 * Pi
        Gamma = 0.068
        h0 = 1.3e-05
    End If
    If Sheets("Model").Shapes("AdvancedCheck").ControlFormat.Value = 1 Then
        If Cells(23, 4).Value = "" Or Cells(24, 4).Value = "" Or Cells(25, 4).Value = "" Or
Cells(26, 4).Value = "" Or Cells(27, 4).Value = "" Or Cells(28, 4).Value = "" Then
            MsgBox ("Input Advanced Parameters or Deselect Advanced Model
Parameters Option")
            Sheets("Model").Protect
            Sheets("Data").Protect
            Exit Sub
        ElseIf Cells(23, 4).Value < 114 Or Cells(23, 4).Value > 120 Or Cells(24, 4).Value <
112.5 Or Cells(24, 4).Value > 114 Or Cells(25, 4).Value < 90 Or Cells(25, 4).Value >
100 Or Cells(26, 4).Value < 20 Or Cells(26, 4).Value > 35 Or Cells(27, 4).Value <
0.052 Or Cells(27, 4).Value > 0.068 Or Cells(28, 4).Value < 1 Or Cells(28, 4).Value >
250 Then
            MsgBox ("Advanced Alloy Parameters out of Range.  Please check advanced
alloy parameter input")
            Sheets("Model").Protect
            Sheets("Data").Protect
            Exit Sub
        ElseIf IsNumeric(Cells(23, 4).Value) = False Or IsNumeric(Cells(24, 4).Value) =
False Or IsNumeric(Cells(25, 4).Value) = False Or IsNumeric(Cells(26, 4).Value) =
False Or IsNumeric(Cells(27, 4).Value) = False Or IsNumeric(Cells(28, 4).Value) =
False Then
            MsgBox ("Input Advanced Parameters or Deselect Advanced Model
Parameters Option")
            Sheets("Model").Protect
            Sheets("Data").Protect
            Exit Sub
        Else
            DmEa = Cells(23, 4).Value
            DbEa = Cells(24, 4).Value
            DsEa = Cells(25, 4).Value
            Theta = Cells(26, 4).Value / 180 * Pi
            Gamma = Cells(27, 4).Value
            h0 = Cells(28, 4).Value * 10 ^ -6
        End If
```

```
    Else
    End If
Else
    MsgBox ("Please select Alloy Input")
    Sheets("Model").Protect
    Sheets("Data").Protect
    Exit Sub
End If

Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)

' Check Other Option Inputs
' If Sheets("Model").Shapes("TestMassLossCheck").ControlFormat.Value = 1 Then
If Sheets("Model").Shapes("RemainingTimeCheck").ControlFormat.Value = 1 Then
    If Cells(37, 4).Value = "" Then
        MsgBox ("Input Current Mass Loss Result or deselect Option")
        Sheets("Model").Protect
        Sheets("Data").Protect
        Exit Sub
    ElseIf Cells(37, 4).Value < 0 Or Cells(37, 4).Value > 40 Then
        MsgBox ("Current Mass Loss Result must be between 0 and 40 mg/cm2.  Please
reenter appropriate value or deselct Option")
        Sheets("Model").Protect
        Sheets("Data").Protect
        Exit Sub
    Else
        ServiceCheck1 = True
        ServiceCheck2 = True
        ServiceML = Sheets("Model").Cells(37, 4).Value
    End If
End If

' Check Graph Inputs
If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = 1 Then
    If Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Or
            Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = 1 Or
            Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = 1 Or
            Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = 1 Then
        If Sheets("Model").Shapes("XTimeCheck").ControlFormat.Value = 1 Then
            Sheets("Data").Cells(1, 6).Value = "Time (Years)"
            GraphXTimeCheck = True
        ElseIf Sheets("Model").Shapes("XTempCheck").ControlFormat.Value = 1 Then
            Sheets("Data").Cells(1, 6).Value = "Average Temperature (F)"
```

```
        If Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) <= 170 And
Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) >= 40 Then
          Sheets("Data").Cells(1, 7).Value = Math.Round((Temp0 - 16 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 8).Value = Math.Round((Temp0 - 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 9).Value = Math.Round((Temp0 - 273) * 9 / 5 + 32,
0)
          Sheets("Data").Cells(1, 10).Value = Math.Round((Temp0 + 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 11).Value = Math.Round((Temp0 + 16 - 273) * 9 / 5
+ 32, 0)
        ElseIf Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) > 170 Then
          Sheets("Data").Cells(1, 7).Value = Math.Round((Temp0 - 32 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 8).Value = Math.Round((Temp0 - 24 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 9).Value = Math.Round((Temp0 - 16 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 10).Value = Math.Round((Temp0 - 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 11).Value = Math.Round((Temp0 - 273) * 9 / 5 + 32,
0)
        ElseIf Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) < 40 Then
          Sheets("Data").Cells(1, 7).Value = Math.Round((Temp0 - 273) * 9 / 5 + 32,
0)
          Sheets("Data").Cells(1, 8).Value = Math.Round((Temp0 + 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 9).Value = Math.Round((Temp0 + 16 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(1, 10).Value = Math.Round((Temp0 + 24 - 273) * 9 / 5
+ 32, 0)
          Sheets("Data").Cells(1, 11).Value = Math.Round((Temp0 + 32 - 273) * 9 / 5
+ 32, 0)
        End If
        GraphXTempCheck = True
      ElseIf Sheets("Model").Shapes("XMgConcCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(1, 6).Value = "Magnesium Concentration (wt%)"
        If Ca0 <= 0.08 And Ca0 >= 0.05 Then
          Sheets("Data").Cells(1, 7).Value = (Ca0 - 0.02) * 100
          Sheets("Data").Cells(1, 8).Value = (Ca0 - 0.01) * 100
          Sheets("Data").Cells(1, 9).Value = Ca0 * 100
          Sheets("Data").Cells(1, 10).Value = (Ca0 + 0.01) * 100
          Sheets("Data").Cells(1, 11).Value = (Ca0 + 0.02) * 100
        ElseIf Ca0 > 0.08 Then
```

```
          Sheets("Data").Cells(1, 7).Value = (Ca0 - 0.04) * 100
          Sheets("Data").Cells(1, 8).Value = (Ca0 - 0.03) * 100
          Sheets("Data").Cells(1, 9).Value = (Ca0 - 0.02) * 100
          Sheets("Data").Cells(1, 10).Value = (Ca0 - 0.01) * 100
          Sheets("Data").Cells(1, 11).Value = Ca0 * 100
        ElseIf Ca0 < 0.05 Then
          Sheets("Data").Cells(1, 7).Value = Ca0 * 100
          Sheets("Data").Cells(1, 8).Value = (Ca0 + 0.01) * 100
          Sheets("Data").Cells(1, 9).Value = (Ca0 + 0.02) * 100
          Sheets("Data").Cells(1, 10).Value = (Ca0 + 0.03) * 100
          Sheets("Data").Cells(1, 11).Value = (Ca0 + 0.04) * 100
        End If
        GraphXMgConcCheck = True
      ElseIf Sheets("Model").Shapes("XGrainCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(1, 6).Value = "Grain Size (um)"
        If h0 <= 200 * 10 ^ -6 And h0 >= 51 * 10 ^ -6 Then
          Sheets("Data").Cells(1, 7).Value = Math.Round((h0 - 50 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 8).Value = Math.Round((h0 - 25 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 9).Value = h0 * 10 ^ 6
          Sheets("Data").Cells(1, 10).Value = Math.Round((h0 + 25 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 11).Value = Math.Round((h0 + 50 * 10 ^ -6) * 10 ^ 6,
0)
        ElseIf h0 > 200 * 10 ^ -6 Then
          Sheets("Data").Cells(1, 7).Value = Math.Round((h0 - 100 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 8).Value = Math.Round((h0 - 75 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 9).Value = Math.Round((h0 - 50 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 10).Value = Math.Round((h0 - 25 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 11).Value = h0 * 10 ^ 6
        ElseIf h0 < 51 * 10 ^ -6 Then
          Sheets("Data").Cells(1, 7).Value = h0 * 10 ^ 6
          Sheets("Data").Cells(1, 8).Value = Math.Round((h0 + 25 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 9).Value = Math.Round((h0 + 50 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 10).Value = Math.Round((h0 + 75 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(1, 11).Value = Math.Round((h0 + 100 * 10 ^ -6) * 10 ^
6, 0)
```

```
        End If
        GraphXGrainCheck = True
      End If
    Else
      MsgBox ("Please Select Graph X-Axis")
      Sheets("Model").Protect
      Sheets("Data").Protect
      Exit Sub
    End If
    If Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Or
          Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = 1 Or
          Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = 1 Or
          Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = 1 Then
      If Sheets("Model").Shapes("YTimeCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(2, 6).Value = "Time (Years)"
        GraphYTimeCheck = True
      ElseIf Sheets("Model").Shapes("YTempCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(2, 6).Value = "Average Temperature (F)"
        If Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) <= 170 And
Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) >= 40 Then
          Sheets("Data").Cells(3, 6).Value = Math.Round((Temp0 - 16 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(4, 6).Value = Math.Round((Temp0 - 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(5, 6).Value = Math.Round((Temp0 - 273) * 9 / 5 + 32,
0)
          Sheets("Data").Cells(6, 6).Value = Math.Round((Temp0 + 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(7, 6).Value = Math.Round((Temp0 + 16 - 273) * 9 / 5 +
32, 0)
        ElseIf Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) > 170 Then
          Sheets("Data").Cells(3, 6).Value = Math.Round((Temp0 - 32 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(4, 6).Value = Math.Round((Temp0 - 24 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(5, 6).Value = Math.Round((Temp0 - 16 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(6, 6).Value = Math.Round((Temp0 - 8 - 273) * 9 / 5 +
32, 0)
          Sheets("Data").Cells(7, 6).Value = Math.Round((Temp0 - 273) * 9 / 5 + 32,
0)
        ElseIf Math.Round((Temp0 - 273) * 9 / 5 + 32, 0) < 40 Then
          Sheets("Data").Cells(3, 6).Value = Math.Round((Temp0 - 273) * 9 / 5 + 32,
0)
```

```
            Sheets("Data").Cells(4, 6).Value = Math.Round((Temp0 + 8 - 273) * 9 / 5 +
32, 0)
            Sheets("Data").Cells(5, 6).Value = Math.Round((Temp0 + 16 - 273) * 9 / 5 +
32, 0)
            Sheets("Data").Cells(6, 6).Value = Math.Round((Temp0 + 24 - 273) * 9 / 5 +
32, 0)
            Sheets("Data").Cells(7, 6).Value = Math.Round((Temp0 + 32 - 273) * 9 / 5 +
32, 0)
        End If
        GraphYTempCheck = True
    ElseIf Sheets("Model").Shapes("YMgConcCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(2, 6).Value = "Magnesium Concentration (wt%)"
        If Ca0 <= 0.08 And Ca0 >= 0.05 Then
            Sheets("Data").Cells(3, 6).Value = (Ca0 - 0.02) * 100
            Sheets("Data").Cells(4, 6).Value = (Ca0 - 0.01) * 100
            Sheets("Data").Cells(5, 6).Value = Ca0 * 100
            Sheets("Data").Cells(6, 6).Value = (Ca0 + 0.01) * 100
            Sheets("Data").Cells(7, 6).Value = (Ca0 + 0.02) * 100
        ElseIf Ca0 > 0.08 Then
            Sheets("Data").Cells(3, 6).Value = (Ca0 - 0.04) * 100
            Sheets("Data").Cells(4, 6).Value = (Ca0 - 0.03) * 100
            Sheets("Data").Cells(5, 6).Value = (Ca0 - 0.02) * 100
            Sheets("Data").Cells(6, 6).Value = (Ca0 - 0.01) * 100
            Sheets("Data").Cells(7, 6).Value = Ca0 * 100
        ElseIf Ca0 < 0.05 Then
            Sheets("Data").Cells(3, 6).Value = Ca0 * 100
            Sheets("Data").Cells(4, 6).Value = (Ca0 + 0.01) * 100
            Sheets("Data").Cells(5, 6).Value = (Ca0 + 0.02) * 100
            Sheets("Data").Cells(6, 6).Value = (Ca0 + 0.03) * 100
            Sheets("Data").Cells(7, 6).Value = (Ca0 + 0.04) * 100
        End If
        GraphYMgConcCheck = True
    ElseIf Sheets("Model").Shapes("YGrainCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(2, 6).Value = "Grain Size (um)"
        If h0 <= 200 * 10 ^ -6 And h0 >= 51 * 10 ^ -6 Then
            Sheets("Data").Cells(3, 6).Value = Math.Round((h0 - 50 * 10 ^ -6) * 10 ^ 6,
0)
            Sheets("Data").Cells(4, 6).Value = Math.Round((h0 - 25 * 10 ^ -6) * 10 ^ 6,
0)
            Sheets("Data").Cells(5, 6).Value = h0 * 10 ^ 6
            Sheets("Data").Cells(6, 6).Value = Math.Round((h0 + 25 * 10 ^ -6) * 10 ^ 6,
0)
            Sheets("Data").Cells(7, 6).Value = Math.Round((h0 + 50 * 10 ^ -6) * 10 ^ 6,
0)
        ElseIf h0 > 200 * 10 ^ -6 Then
```

```
          Sheets("Data").Cells(3, 6).Value = Math.Round((h0 - 100 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(4, 6).Value = Math.Round((h0 - 75 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(5, 6).Value = Math.Round((h0 - 50 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(6, 6).Value = Math.Round((h0 - 25 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(7, 6).Value = h0 * 10 ^ 6
        ElseIf h0 < 501 * 10 ^ -6 Then
          Sheets("Data").Cells(3, 6).Value = h0 * 10 ^ 6
          Sheets("Data").Cells(4, 6).Value = Math.Round((h0 + 25 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(5, 6).Value = Math.Round((h0 + 50 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(6, 6).Value = Math.Round((h0 + 75 * 10 ^ -6) * 10 ^ 6,
0)
          Sheets("Data").Cells(7, 6).Value = Math.Round((h0 + 100 * 10 ^ -6) * 10 ^ 6,
0)
        End If
        GraphYGrainCheck = True
      End If
    Else
      MsgBox ("Please Select Graph Y-Axis")
      Sheets("Model").Protect
      Sheets("Data").Protect
      Exit Sub
    End If
    If Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = 1 Or
Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = 1 Then
      If Sheets("Model").Shapes("ZMLCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(2, 7).Value = "Mass Loss (mg/cm2)"
        GraphZMLCheck = True
      ElseIf Sheets("Model").Shapes("ZThresholdCheck").ControlFormat.Value = 1
Then
        Sheets("Data").Cells(2, 7).Value = "Time to Threshold Sensitization (Years)"
        GraphZThresholdCheck = True
      ElseIf Sheets("Model").Shapes("ZHighCheck").ControlFormat.Value = 1 Then
        Sheets("Data").Cells(2, 7).Value = "Time to High Sensitization (Years)"
        GraphZHighCheck = True
      End If
    Else
      MsgBox ("Please Select Graph Z-Axis")
      Sheets("Model").Protect
```

```
    Sheets("Data").Protect
    Exit Sub
  End If
End If

' Section 2 - Model mathematics for multiple data points
If Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = 1 Then

  ' Part I - Assign Values
  Do
  GraphTimeLoop = 0
  time = 1
  dt = 1
  Omega = 1e-05
  Ca = Ca0
  Cab = 0.029
  Cb = 0.3
  Cs = (Cb + Cab) / 2
  h = h0
  Delta = 5e-10
  vat = 1.66e-29
  k = 1.381e-23
  a0 = 4.05e-10
  N0 = 6.02e+28
  Yita = 1.05
  i = 1
  R = 1.5e-09
  N = 5000000000#
  A = Pi * (R + 2 * (Db * time) ^ 0.5) ^ 2
  Rc = (A / Pi) ^ 0.5
  SensitizedCheck = True
  FailureCheck = False
  GRate = 5 / (86400 * 0.5 * 2700)
  BRate = 45 / (86400 * 0.5 * 2700)
  PRate = (GRate + 2 * BRate) / 3
  PreBetaFraction = 0.45
  MLThetaCutoff = 1 / (1 + 2 * PreBetaFraction)
  BetaTheta = 0
  ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) * PRate *
BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta * GRate *
PRate) * 86400 * 0.5 * 2700 ' Mass loss

  If GraphXTempCheck = True Then
    If GraphXLoop = 0 Then
      Temp0 = Temp00
```

```
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) <= 170 And
Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) >= 40 Then
        Temp0 = Temp00 - 16 + 8 * (GraphXLoop - 1)
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) > 170 Then
        Temp0 = Temp00 - 32 + 8 * (GraphXLoop - 1)
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) < 40 Then
        Temp0 = Temp00 + 8 * (GraphXLoop - 1)
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      End If
    ElseIf GraphXMgConcCheck = True Then
      If GraphXLoop = 0 Then
        Ca = Ca0
        DsEa = -142.86 * Ca + 104.29
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Ca0 <= 0.08 And Ca0 >= 0.05 Then
        Ca = Ca0 - 0.02 + 0.01 * (GraphXLoop - 1)
        DsEa = -142.86 * Ca + 104.29
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Ca0 > 0.08 Then
        Ca = Ca0 - 0.04 + 0.01 * (GraphXLoop - 1)
        DsEa = -142.86 * Ca + 104.29
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Ca0 < 0.05 Then
        Ca = Ca0 + 0.01 * (GraphXLoop - 1)
        DsEa = -142.86 * Ca + 104.29
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      End If
    ElseIf GraphXGrainCheck = True Then
      If GraphXLoop = 0 Then
        h = h0
```

```
      ElseIf h0 <= 200 * 10 ^ -6 And h0 >= 51 * 10 ^ -6 Then
        h = h0 - 50 * 10 ^ -6 + 25 * 10 ^ -6 * (GraphXLoop - 1)
      ElseIf h0 > 200 * 10 ^ -6 Then
        h = h0 - 100 * 10 ^ -6 + 25 * 10 ^ -6 * (GraphXLoop - 1)
      ElseIf h0 < 51 * 10 ^ -6 Then
        h = h0 + 25 * 10 ^ -6 * (GraphXLoop - 1)
      End If
    End If

    If GraphYTempCheck = True Then
      If GraphYLoop = 0 Then
        Temp0 = Temp00
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) <= 170 And
  Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) >= 40 Then
        Temp0 = Temp00 - 16 + 8 * (GraphYLoop - 1)
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) > 170 Then
        Temp0 = Temp00 - 32 + 8 * (GraphYLoop - 1)
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Math.Round((Temp00 - 273) * 9 / 5 + 32, 0) < 40 Then
        Temp0 = Temp00 + 8 * (GraphYLoop - 1)
        T = Temp0
        Dm = (1.49e-05) * Exp(-DmEa * 1000 / 8.314 / T)
        Db = (6.5e-05) * Exp(-DbEa * 1000 / 8.314 / T)
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      End If
    ElseIf GraphYMgConcCheck = True Then
      If GraphYLoop = 0 Then
        Ca = Ca0
        DsEa = -142.86 * Ca + 104.29
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
      ElseIf Ca0 <= 0.08 And Ca0 >= 0.05 Then
        Ca = Ca0 - 0.02 + 0.01 * (GraphYLoop - 1)
        DsEa = -142.86 * Ca + 104.29
        Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
```

```
    ElseIf Ca0 > 0.08 Then
      Ca = Ca0 - 0.04 + 0.01 * (GraphYLoop - 1)
      DsEa = -142.86 * Ca + 104.29
      Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
    ElseIf Ca0 < 0.05 Then
      Ca = Ca0 + 0.01 * (GraphYLoop - 1)
      DsEa = -142.86 * Ca + 104.29
      Ds = (4.5e-05) * Exp(-DsEa * 1000 / 8.314 / T)
    End If
  ElseIf GraphYGrainCheck = True Then
    If GraphXLoop = 0 Then
      h = h0
    ElseIf h0 <= 200 * 10 ^ -6 And h0 >= 51 * 10 ^ -6 Then
      h = h0 - 50 * 10 ^ -6 + 25 * 10 ^ -6 * (GraphYLoop - 1)
    ElseIf h0 > 200 * 10 ^ -6 Then
      h = h0 - 100 * 10 ^ -6 + 25 * 10 ^ -6 * (GraphYLoop - 1)
    ElseIf h0 < 51 * 10 ^ -6 Then
      h = h0 + 25 * 10 ^ -6 * (GraphYLoop - 1)
    End If
  End If

  BetaTheta = Rc / (1 * 10 ^ -7)
  ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) * PRate *
BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta * GRate *
PRate) * 86400 * 0.5 * 2700

  ' Part II - Solute flow to the grain boundary
  'Short Term
  If time < 200000000# Then
    Jms = (Ca - Cab) * (Dm ^ 0.5) / ((Pi * time) ^ 0.5)
    J = Jms

  ' Long term
  Else
    ni = 0
    ani = 0
    Sumni = 0

    Do While (ni < 20)
      ani = Exp(-(((2 * ni + 1) * Pi / h) ^ 2) * Dm * time)
      Sumni = Sumni + ani
      ni = ni + 1
    Loop

    Jml = 4 * (Ca - Cab) * Dm / h * Sumni
```

```
    J = Jml
  End If

  ' Part III - Initial volume of the precipitate
  Js = ((A - Pi * R * R) / (2 * Pi * R * Delta / 2)) * J
  Rsu = (1 / 3 * (1 + (4 + 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R /
Sin(Theta)) ^ 0.5)) ^ 0.5
  If Rsu < 1.00000000000001 Then
    Rsu = 1.00000000000001
  End If
  Cosga = Cos(Theta) / Rsu
  V0 = Tan(Theta) * (1 - 1 / (1 + Cosga) ^ 2)

  ' Part IV - Heterogeneous nucleaton rate at grain boundary
    ' Geometry of the precipitate
  fPV = Pi * Tan(Theta) / 3 * (1 - 1 / (1 + Cosga) ^ 2)
  Aa = 1 / (1 - Cosga * Cosga) ^ 0.5
  Bb = Tan(Theta) * (Cosga) / (1 - Cosga * Cosga)
  Cc = Bb * (1 - Cosga)
  Dd = Cosga * Cosga / (1 - Cosga * Cosga) * Tan(Theta)
  e = (1 - (Tan(Theta) * Tan(Theta) * Cosga * Cosga / (1 - Cosga * Cosga))) ^ 0.5
  fPA = Pi / Bb / Bb / e * (Bb * Bb * (e * Aa * Aa + Bb * Bb * Log((1 + e) * Aa * Bb * R *
R)) - Aa * Dd * e * ((Aa * Dd * e) ^ 2 + Bb ^ 4) ^ 0.5 - (Bb ^ 4) * Log(Aa * Dd * e * R * R
+ (Bb ^ 4 * (R ^ 4) + (Aa * Dd * e * R * R) ^ 2) ^ 0.5))

  ' Part V - Concentration along the grain boundary
  Ri = R
  Kc = 2 * fPA / 3 / fPV / R
  CRi = Cab * Exp(Gamma * vat / k / T * Kc)
  CRx = CRi + J / Delta / Db * (Ri * Ri / 2 - Rc * Rc * Log(Ri)) + J / Delta / Db / (Rc -
Ri) * (Rc * Rc * Rc * (Log(Rc) - 7 / 6) - Ri * (Rc * Rc * Log(Ri) - Rc * Rc - Ri * Ri  / 6))
  Deltag = -k * T / vat * Log(CRx / Cab)
  Rs = -2 / 3 * fPA / fPV * Gamma / Deltag
  DeltaGs = 4 / 27 * fPA * fPA * fPA / fPV / fPV * Gamma * Gamma * Gamma / Deltag
/ Deltag
  Zed = vat / 2 / Pi / (Rs * Rs) * (Gamma / k / T) ^ 0.5
  Betas = 4 * Pi * Rs * Rs * Db * CRx / (a0) ^ 4
  Tao0 = 4 / 2 / Pi / Betas / Zed / Zed
  Rdta = 1 / (1 - Cosga * Cosga) - (Cosga * Cosga / (1 - Cosga ^ 2) + (Delta ^ 2) / 4 /
(R * R) * (1 - Cosga ^ 2) / (Cosga * Cosga) / (Tan(Theta)) ^ 2 + Delta / R /
Tan(Theta))

  If (Cc * R < (Delta / 2)) Then
    Vp = fPV * (R ^ 3)
  Else
```

```
    Vp = Pi * ((R + R * Rdta ^ 0.5) / 2) ^ 2 * Delta / 2
  End If

  Vavl = Delta / 2 - N * Vp
  favl = 2 * Vavl / Delta
  dNn = Delta * Delta / h * favl * N0 * Zed * Betas * Exp(-DeltaGs * 1 / k / T) * Exp(-
Tao0 / time)
  time = time + dt

  ' Part VI - Precipitate Growth over time
  Do While (i < 100000000)
    T = TempA * Sin(Pi / 43200 * time) + Temp0

    ' Short term
    If time < 200000000# Then
      Jms = (Ca - Cab) * (Dm ^ 0.5) / ((Pi * time) ^ 0.5)
      J = Jms

    ' Long term
    Else
      ni = 0
      ani = 0
      Sumni = 0
      Do While (ni < 20)
        ani = Exp(-(((2 * ni + 1) * Pi / h) ^ 2) * Dm * time)
        Sumni = Sumni + ani
        ni = ni + 1
      Loop
      Jml = 4 * (Ca - Cab) * Dm / h * Sumni
      J = Jml
    End If

    fPV = Pi * Tan(Theta) / 3 * (1 - 1 / (1 + Cosga) ^ 2)
    Aa = 1 / (1 - Cosga * Cosga) ^ 0.5
    Bb = Tan(Theta) * (Cosga) / (1 - Cosga * Cosga)
    Cc = Bb * (1 - Cosga)
    Dd = Cosga * Cosga / (1 - Cosga * Cosga) * Tan(Theta)
    e = (1 - (Tan(Theta) * Tan(Theta) * Cosga * Cosga / (1 - Cosga * Cosga))) ^ 0.5
    fPA = Pi / Bb / Bb / e * (Bb * Bb * (e * Aa * Aa + Bb * Bb * Log((1 + e) * Aa * Bb *
R * R)) - Aa * Dd * e * ((Aa * Dd * e) ^ 2 + Bb ^ 4) ^ 0.5 - Bb ^ 4 * Log(Aa * Dd * e * R *
R + (Bb ^ 4 * R ^ 4 + (Aa * Dd * e * R * R) ^ 2) ^ 0.5))
    Deltag = -k * T / vat * Log(CRx / Cab)
    Rs = -2 / 3 * fPA / fPV * Gamma / Deltag
    DeltaGs = 4 / 27 * fPA * fPA * fPA / fPV / fPV * Gamma * Gamma * Gamma /
Deltag / Deltag
```

```
    Zed = vat / 2 / Pi / (Rs * Rs) * (Gamma / k / T) ^ 0.5
    Betas = 4 * Pi * Rs * Rs * Db * CRx / (a0) ^ 4
    Tao0 = 4 / 2 / Pi / Betas / Zed / Zed
    Rdta = 1 / (1 - Cosga * Cosga) - (Cosga * Cosga / (1 - Cosga ^ 2) + (Delta ^ 2) / 4
/ (R * R) * (1 - Cosga ^ 2) / (Cosga * Cosga) / (Tan(Theta)) ^ 2 + Delta / R /
Tan(Theta))

    If (Cc * R < (Delta / 2)) Then
      Vp = fPV * R ^ 3
    Else
      Vp = Pi * (((R + R * Rdta ^ 0.5) / 2) ^ 2) * Delta / 2
    End If

    Vavl = Delta / 2 - N * Vp
    favl = 2 * Vavl / Delta
    dNn = Delta * Delta / h * favl * N0 * Zed * Betas * Exp(-DeltaGs * 1 / k / T) *
Exp(-Tao0 / time)
    Js = (((A - Pi * R * R) / (2 * Pi * R * Delta / 2)) * J - dNn * N * (A - Pi * R * R) / (1 -
N * Pi * R * R) * fPV * Rs ^ 3 / N / (Pi * R * Delta) * (Cb - Cab))
    If 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R / Sin(Theta) < -4 Then
      Js = -4 / (3 * 8.314 * T / Ds / Cs / Gamma / Omega * R * R / Sin(Theta)) + 1e-
14
    End If
    Rsu = (1 / 3 * (1 + (4 + 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R /
Sin(Theta)) ^ 0.5)) ^ 0.5
    If Rsu < 1.00000000000001 Then
      Rsu = 1.00000000000001
    End If
    Cosga = Cos(Theta) / Rsu
    V1 = Tan(Theta) * (1 - 1 / (1 + Cosga) ^ 2)
    Ri = R
    Kc = 2 * fPA / 3 / fPV / R
    CRi = Cab * Exp(Gamma * vat / k / T * Kc)
    CRx = CRi + J / Delta / Db * (Ri * Ri / 2 - Rc * Rc * Log(Ri)) + J / Delta / Db / (Rc -
Ri) * (Rc * Rc * Rc * (Log(Rc) - 7 / 6) - Ri * (Rc * Rc * Log(Ri) - Rc * Rc - Ri * Ri  / 6))

    ' Precipitate growth rate
    dVg = J * A / (Cb - Cab) - dNn * (Yita * fPV * Rs ^ 3) / N

    ' Coarsening rate
    Alpha = (2 * fPA * Gamma / 3 / fPV / k / T) * vat * Cab
    dVc = 4 / 9 * fPA * Alpha * Db / (Cb - Cab)

    ' Coarsening fraction
    fcoa = dVc / (dVg + dVc)
```

```
' Final growth rate
dVf = fcoa * dVc + (1 - fcoa) * dVg

' Precipitate number change during the coarsening
dNc = J / (fPV * R ^ 3) / (Cb - Cab) - N / (fPV * R ^ 3) * dVc

' Radius change rate
dVm = (V1 - V0) / dt
dRf = 1 / (Pi * V1 * R * R) * dVf - R / 3 / V1 * dVm

' Total number change rate
If (-dNc) > dNn Then
  dN = fcoa * dNc
Else
  dN = dNn
End If

R1 = R + dRf * dt
N = N + dN * dt
A1 = A + 4 * Pi * Db * dt
A2 = 1 / N

If A1 > A2 Then
  A = A2
Else
  A = A1
End If

Rc = (A / Pi) ^ 0.5
time = time + dt
If R1 > 0 Then
  R = R1
End If
V0 = V1
i = i + 1
BetaTheta = R / ((A2 / Pi) ^ 0.5)
ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700

' Part VII - Final data and graphed data output
If 25 < ML And SensitizedCheck = True Then
  SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
  SensitizedCheck = False
```

```
    End If

    If GraphXTimeCheck = True And GraphZMLCheck = True Then
      If GraphXLoop = 0 Then
      ElseIf GraphTimeLoop > 4 Then
        Exit Do
      ElseIf time / 3600 / 24 / 30 / 12 > Sheets("Data").Cells(GraphYStart - 2,
       GraphXStart + GraphTimeLoop).Value And GraphTimeCheck = True Then
        Sheets("Data").Cells(GraphYStart + GraphXLoop - 1, GraphXStart +
GraphTimeLoop).Value = Math.Round(ML, 2)
        GraphTimeCheck = False
        GraphTimeLoop = GraphTimeLoop + 1
      ElseIf 40 < ML Then
        Do
          Sheets("Data").Cells(GraphYStart + GraphXLoop - 1, GraphXStart +
GraphTimeLoop).Value = Math.Round(ML, 2)
          GraphTimeCheck = False
          GraphTimeLoop = GraphTimeLoop + 1
        Loop Until GraphTimeLoop > 4
      ElseIf time > 3.11 * 10 ^ 10 Then
        Sheets("Data").Cells(GraphYStart + GraphXLoop - 1, GraphXStart +
GraphTimeLoop).Value = Math.Round(ML, 2)
        GraphTimeCheck = False
        GraphTimeLoop = GraphTimeLoop + 1
      ElseIf time / 3600 / 24 / 30 / 12 > Sheets("Data").Cells(GraphYStart - 2,
GraphXStart + GraphTimeLoop).Value - 0.05 Then
        GraphTimeCheck = True
      End If
    End If

    If GraphYTimeCheck = True And GraphZMLCheck = True Then
      If GraphYLoop = 0 Then
      ElseIf GraphTimeLoop > 4 Then
        Exit Do
      ElseIf time / 3600 / 24 / 30 / 12 > Sheets("Data").Cells(GraphYStart +
GraphTimeLoop, GraphXStart - 1).Value And GraphTimeCheck = True Then
        Sheets("Data").Cells(GraphYStart + GraphTimeLoop, GraphXStart +
GraphYLoop - 1).Value = Math.Round(ML, 2)
        GraphTimeCheck = False
        GraphTimeLoop = GraphTimeLoop + 1
      ElseIf 40 < ML Then
        Do
          Sheets("Data").Cells(GraphYStart + GraphTimeLoop, GraphXStart +
GraphYLoop - 1).Value = Math.Round(ML, 2)
          GraphTimeCheck = False
```

```
          GraphTimeLoop = GraphTimeLoop + 1
        Loop Until GraphTimeLoop > 4
      ElseIf time > 3.11 * 10 ^ 10 Then
        Sheets("Data").Cells(GraphYStart + GraphTimeLoop, GraphXStart +
GraphYLoop - 1).Value = Math.Round(ML, 2)
        GraphTimeCheck = False
        GraphTimeLoop = GraphTimeLoop + 1
      ElseIf time / 3600 / 24 / 30 / 12 > Sheets("Data").Cells(GraphYStart +
GraphTimeLoop, GraphXStart - 1).Value - 0.05 Then
        GraphTimeCheck = True
      End If
    End If

    If ServiceML < ML And ServiceCheck1 = True Then
      ServiceTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
      ServiceCheck1 = False
    End If

    If 40 < ML Then
      FailureCheck = True
      Exit Do
    End If

    If ML0 > ML - 0.001 Then
      dt = dt * 2
    ElseIf ML0 < ML - 0.002 Then
      dt = Round(dt / 2, 0)
      If dt < 1 Then
        dt = 1
      End If
    End If

    If GraphXTimeCheck = True And GraphZMLCheck = True Then
      If GraphXLoop = 0 Then
      ElseIf (time + dt) / 3600 / 24 / 30 / 12 > Sheets("Data").Cells(GraphYStart - 2,
GraphXStart + GraphTimeLoop).Value Then
        dt = 1
      End If
    End If
    If GraphYTimeCheck = True And GraphZMLCheck = True Then
      If GraphYLoop = 0 Then
      ElseIf (time + dt) / 3600 / 24 / 30 / 12 > Sheets("Data").Cells(GraphYStart +
GraphTimeLoop, GraphXStart - 1).Value Then
        dt = 1
      End If
```

```
    End If

    ML0 = ML

    If time > 3.11 * 10 ^ 10 Then
      Exit Do
    End If

    Loop

  FailureTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
  If FailureTime <= 0.02 Then
    FailureTime = 0.02
  End If

  If GraphXLoop = 0 And GraphYLoop = 0 Then
    If GraphXTimeCheck = True Then
      If SensitizedCheck = True Or FailureCheck = False Then
        Sheets("Data").Cells(1, 7).Value = 100
        Sheets("Data").Cells(1, 8).Value = 250
        Sheets("Data").Cells(1, 9).Value = 500
        Sheets("Data").Cells(1, 10).Value = 750
        Sheets("Data").Cells(1, 11).Value = 1000
      ElseIf FailureTime = 0.02 Then
        Sheets("Data").Cells(1, 7).Value = 0.01
        Sheets("Data").Cells(1, 8).Value = 0.02
        Sheets("Data").Cells(1, 9).Value = 0.03
        Sheets("Data").Cells(1, 10).Value = 0.04
        Sheets("Data").Cells(1, 11).Value = 0.05
      Else
        Sheets("Data").Cells(1, 7).Value = Math.Round(SensitizedTime / 4, 2)
        Sheets("Data").Cells(1, 8).Value = Math.Round(2 * SensitizedTime / 3, 2)
        Sheets("Data").Cells(1, 9).Value = SensitizedTime
        Sheets("Data").Cells(1, 10).Value = Math.Round((FailureTime +
       SensitizedTime) / 2, 2)
        Sheets("Data").Cells(1, 11).Value = FailureTime
      End If
    ElseIf GraphYTimeCheck = True Then
      If SensitizedCheck = True Or FailureCheck = False Then
        Sheets("Data").Cells(3, 6).Value = 100
        Sheets("Data").Cells(4, 6).Value = 250
        Sheets("Data").Cells(5, 6).Value = 500
        Sheets("Data").Cells(6, 6).Value = 750
        Sheets("Data").Cells(7, 6).Value = 1000
      ElseIf FailureTime = 0.02 Then
```

```
            Sheets("Data").Cells(3, 6).Value = 0.01
            Sheets("Data").Cells(4, 6).Value = 0.02
            Sheets("Data").Cells(5, 6).Value = 0.03
            Sheets("Data").Cells(6, 6).Value = 0.04
            Sheets("Data").Cells(7, 6).Value = 0.05
        Else
            Sheets("Data").Cells(3, 6).Value = Math.Round(SensitizedTime / 4, 2)
            Sheets("Data").Cells(4, 6).Value = Math.Round(2 * SensitizedTime / 3, 2)
            Sheets("Data").Cells(5, 6).Value = SensitizedTime
            Sheets("Data").Cells(6, 6).Value = Math.Round((FailureTime +
         SensitizedTime) / 2, 2)
            Sheets("Data").Cells(7, 6).Value = FailureTime
        End If
    End If
    If GraphXLoop = 0 And GraphYLoop = 0 Then
        If ServiceCheck2 = True Then
            Cells(4, 11).Value = "Time Remaining to Threshold Sensitization, 25
mg/cm2 "
            Cells(5, 11).Value = "Time Remaining to High Sensitization, 40 mg/cm2 "
            If SensitizedTime - ServiceTime < 0 Then
                Cells(4, 13).Value = 0
            Else
                Cells(4, 13).Value = SensitizedTime - ServiceTime
            End If
            If FailureTime - ServiceTime < 0 Then
                Cells(5, 13).Value = 0
            Else
                Cells(5, 13).Value = FailureTime - ServiceTime
            End If
        Else
            Cells(4, 11).Value = "Time to Threshold Sensitization, 25 mg/cm2 "
            Cells(5, 11).Value = "Time to High Sensitization, 40 mg/cm2 "
            If SensitizedCheck = True Then
                Cells(4, 13).Value = ">1000"
                Cells(5, 13).Value = ">1000"
            ElseIf FailureCheck = False Then
                Cells(4, 13).Value = SensitizedTime
                Cells(5, 13).Value = ">1000"
            Else
                Cells(4, 13).Value = SensitizedTime
                Cells(5, 13).Value = FailureTime

            End If
        End If
    End If
```

```
    End If

    If GraphZThresholdCheck = True Then
      If GraphXLoop = 0 Then
      ElseIf SensitizedCheck = True Then
        Sheets("Data").Cells(GraphYStart + GraphYLoop - 1, GraphXStart +
GraphXLoop - 1).Value = 1000
      Else
        Sheets("Data").Cells(GraphYStart + GraphYLoop - 1, GraphXStart +
GraphXLoop - 1).Value = SensitizedTime
      End If
    ElseIf GraphZHighCheck = True Then
      If GraphXLoop = 0 Then
      ElseIf FailureCheck = False Then
        Sheets("Data").Cells(GraphYStart + GraphYLoop - 1, GraphXStart +
GraphXLoop - 1).Value = 1000
      Else
        Sheets("Data").Cells(GraphYStart + GraphYLoop - 1, GraphXStart +
GraphXLoop - 1).Value = FailureTime
      End If
    End If

    If GraphZThresholdCheck = True Or GraphZHighCheck = True Then
      If GraphYLoop < 5 Then
        GraphYLoop = GraphYLoop + 1
      ElseIf GraphYLoop = 5 Then
        GraphXLoop = GraphXLoop + 1
        GraphYLoop = 1
      End If
    Else
      GraphXLoop = GraphXLoop + 1
      GraphYLoop = GraphYLoop + 1
    End If
Loop Until GraphXLoop > 5

' Section 3 - Model mathematics for a single data point
ElseIf Sheets("Model").Shapes("GraphCheck").ControlFormat.Value = -4146 Then

    ' Part I - Assign Values
    time = 1
    dt = 1
    Omega = 1e-05
    Ca = Ca0
    Cab = 0.029
    Cb = 0.3
```

```
    Cs = (Cb + Cab) / 2
    h = h0
    Delta = 5e-10
    vat = 1.66e-29
    k = 1.381e-23
    a0 = 4.05e-10
    N0 = 6.02e+28
    Yita = 1.05
    i = 1
    R = 1.5e-09
    N = 5000000000#
    A = Pi * (R + 2 * (Db * time) ^ 0.5) ^ 2
    Rc = (A / Pi) ^ 0.5
    SensitizedCheck = True
    FailureCheck = False
    GRate = 5 / (86400 * 0.5 * 2700)
    BRate = 45 / (86400 * 0.5 * 2700)
    PRate = (1 * GRate + 2 * BRate) / 3
    PreBetaFraction = 0.45
    MLThetaCutoff = 1 / (1 + 2 * PreBetaFraction)
    BetaTheta = Rc / (1 * 10 ^ -7)
    ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) * PRate *
BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta * GRate *
PRate) * 86400 * 0.5 * 2700

    ' Part II - Solute flow to the grain boundary
    ' Short term
    If time < 200000000# Then
        Jms = (Ca - Cab) * (Dm ^ 0.5) / ((Pi * time) ^ 0.5)
        J = Jms

    ' Long term
    Else
        ni = 0
        ani = 0
        Sumni = 0

        Do While (ni < 20)
            ani = Exp(-((((2 * ni + 1) * Pi / h) ^ 2) * Dm * time)
            Sumni = Sumni + ani
            ni = ni + 1
        Loop

        Jml = 4 * (Ca - Cab) * Dm / h * Sumni
        J = Jml
```

```
    End If

    ' Part III - Initial volume of the precipitate
    Js = ((A - Pi * R * R) / (2 * Pi * R * Delta / 2)) * J
    Rsu = (1 / 3 * (1 + (4 + 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R /
Sin(Theta)) ^ 0.5)) ^ 0.5
    If Rsu < 1.00000000000001 Then
        Rsu = 1.00000000000001
    End If
    Cosga = Cos(Theta) / Rsu
    V0 = Tan(Theta) * (1 - 1 / (1 + Cosga) ^ 2)

    ' Part IV - Heterogeneous nucleaton rate at grain boundary
        ' Geometry of the precipitate
    fPV = Pi * Tan(Theta) / 3 * (1 - 1 / (1 + Cosga) ^ 2)
    Aa = 1 / (1 - Cosga * Cosga) ^ 0.5
    Bb = Tan(Theta) * (Cosga) / (1 - Cosga * Cosga)
    Cc = Bb * (1 - Cosga)
    Dd = Cosga * Cosga / (1 - Cosga * Cosga) * Tan(Theta)
    e = (1 - (Tan(Theta) * Tan(Theta) * Cosga * Cosga / (1 - Cosga * Cosga))) ^ 0.5
    fPA = Pi / Bb / Bb / e * (Bb * Bb * (e * Aa * Aa + Bb * Bb * Log((1 + e) * Aa * Bb * R *
R)) - Aa * Dd * e * ((Aa * Dd * e) ^ 2 + Bb ^ 4) ^ 0.5 - (Bb ^ 4) * Log(Aa * Dd * e * R * R
+ (Bb ^ 4 * (R ^ 4) + (Aa * Dd * e * R * R) ^ 2) ^ 0.5))

    ' Part V - Concentration along the grain boundary
    Ri = R
    Kc = 2 * fPA / 3 / fPV / R
    CRi = Cab * Exp(Gamma * vat / k / T * Kc)
    CRx = CRi + J / Delta / Db * (Ri * Ri / 2 - Rc * Rc * Log(Ri)) + J / Delta / Db / (Rc -
Ri) * (Rc * Rc * Rc * (Log(Rc) - 7 / 6) - Ri * (Rc * Rc * Log(Ri) - Rc * Rc - Ri * Ri / 6))
    Deltag = -k * T / vat * Log(CRx / Cab)
    Rs = -2 / 3 * fPA / fPV * Gamma / Deltag
    DeltaGs = 4 / 27 * fPA * fPA * fPA / fPV / fPV * Gamma * Gamma * Gamma / Deltag
/ Deltag
    Zed = vat / 2 / Pi / (Rs * Rs) * (Gamma / k / T) ^ 0.5
    Betas = 4 * Pi * Rs * Rs * Db * CRx / (a0) ^ 4
    Tao0 = 4 / 2 / Pi / Betas / Zed / Zed
    Rdta = 1 / (1 - Cosga * Cosga) - (Cosga * Cosga / (1 - Cosga ^ 2) + (Delta ^ 2) / 4 /
(R * R) * (1 - Cosga ^ 2) / (Cosga * Cosga) / (Tan(Theta)) ^ 2 + Delta / R /
Tan(Theta))

    If (Cc * R < (Delta / 2)) Then
        Vp = fPV * (R ^ 3)
    Else
        Vp = Pi * ((R + R * Rdta ^ 0.5) / 2) ^ 2 * Delta / 2
```

```
   End If

   Vavl = Delta / 2 - N * Vp
   favl = 2 * Vavl / Delta
   dNn = Delta * Delta / h * favl * N0 * Zed * Betas * Exp(-DeltaGs * 1 / k / T) * Exp(-
Tao0 / time)
   time = time + dt

   ' Part VI - Precipitate Growth over time,
   Do While (i < 100000000#)

      T = TempA * Sin(Pi / 43200 * time) + Temp0 '

      ' Short term
      If time < 200000000# Then
         Jms = (Ca - Cab) * (Dm ^ 0.5) / ((Pi * time) ^ 0.5)
         J = Jms

      ' Long term
      Else
         ni = 0
         ani = 0
         Sumni = 0
         Do While (ni < 20)
            ani = Exp(-(((2 * ni + 1) * Pi / h) ^ 2) * Dm * time)
            Sumni = Sumni + ani
            ni = ni + 1
         Loop
         Jml = 4 * (Ca - Cab) * Dm / h * Sumni
         J = Jml
      End If

      fPV = Pi * Tan(Theta) / 3 * (1 - 1 / (1 + Cosga) ^ 2)
      Aa = 1 / (1 - Cosga * Cosga) ^ 0.5
      Bb = Tan(Theta) * (Cosga) / (1 - Cosga * Cosga)
      Cc = Bb * (1 - Cosga)
      Dd = Cosga * Cosga / (1 - Cosga * Cosga) * Tan(Theta)
      e = (1 - (Tan(Theta) * Tan(Theta) * Cosga * Cosga / (1 - Cosga * Cosga))) ^ 0.5
      fPA = Pi / Bb / Bb / e * (Bb * Bb * (e * Aa * Aa + Bb * Bb * Log((1 + e) * Aa * Bb *
R * R)) - Aa * Dd * e * ((Aa * Dd * e) ^ 2 + Bb ^ 4) ^ 0.5 - Bb ^ 4 * Log(Aa * Dd * e * R *
R + (Bb ^ 4 * R ^ 4 + (Aa * Dd * e * R * R) ^ 2) ^ 0.5))
      Deltag = -k * T / vat * Log(CRx / Cab)
      Rs = -2 / 3 * fPA / fPV * Gamma / Deltag
      DeltaGs = 4 / 27 * fPA * fPA * fPA / fPV / fPV * Gamma * Gamma * Gamma /
Deltag / Deltag
```

```
Zed = vat / 2 / Pi / (Rs * Rs) * (Gamma / k / T) ^ 0.5
Betas = 4 * Pi * Rs * Rs * Db * CRx / (a0) ^ 4
Tao0 = 4 / 2 / Pi / Betas / Zed / Zed
Rdta = 1 / (1 - Cosga * Cosga) - (Cosga * Cosga / (1 - Cosga ^ 2) + (Delta ^ 2) / 4
/ (R * R) * (1 - Cosga ^ 2) / (Cosga * Cosga) / (Tan(Theta)) ^ 2 + Delta / R /
Tan(Theta))

If (Cc * R < (Delta / 2)) Then
  Vp = fPV * R ^ 3
Else
  Vp = Pi * (((R + R * Rdta ^ 0.5) / 2) ^ 2) * Delta / 2
End If

Vavl = Delta / 2 - N * Vp
favl = 2 * Vavl / Delta
dNn = Delta * Delta / h * favl * N0 * Zed * Betas * Exp(-DeltaGs * 1 / k / T) *
Exp(-Tao0 / time)
Js = (((A - Pi * R * R) / (2 * Pi * R * Delta / 2)) * J - dNn * N * (A - Pi * R * R) / (1 -
N * Pi * R * R) * fPV * Rs ^ 3 / N / (Pi * R * Delta) * (Cb - Cab))
If 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R / Sin(Theta) < -4 Then
   Js = -4 / (3 * 8.314 * T / Ds / Cs / Gamma / Omega * R * R / Sin(Theta)) + 1e-
14
End If
Rsu = (1 / 3 * (1 + (4 + 3 * Js * 8.314 * T / Ds / Cs / Gamma / Omega * R * R /
   Sin(Theta)) ^ 0.5)) ^ 0.5
If Rsu < 1.00000000000001 Then
  Rsu = 1.00000000000001
End If
Cosga = Cos(Theta) / Rsu
V1 = Tan(Theta) * (1 - 1 / (1 + Cosga) ^ 2)
Ri = R
Kc = 2 * fPA / 3 / fPV / R
CRi = Cab * Exp(Gamma * vat / k / T * Kc)
CRx = CRi + J / Delta / Db * (Ri * Ri / 2 - Rc * Rc * Log(Ri)) + J / Delta / Db / (Rc -
Ri) * (Rc * Rc * Rc * (Log(Rc) - 7 / 6) - Ri * (Rc * Rc * Log(Ri) - Rc * Rc - Ri * Ri / 6))

' Precipitate growth rate
dVg = J * A / (Cb - Cab) - dNn * (Yita * fPV * Rs ^ 3) / N

' Coarsening rate
Alpha = (2 * fPA * Gamma / 3 / fPV / k / T) * vat * Cab
dVc = 4 / 9 * fPA * Alpha * Db / (Cb - Cab)

' Coarsening fraction
fcoa = dVc / (dVg + dVc)
```

```
' Final growth rate
dVf = fcoa * dVc + (1 - fcoa) * dVg

' Precipitate number change during the coarsening
dNc = J / (fPV * R ^ 3) / (Cb - Cab) - N / (fPV * R ^ 3) * dVc

' Radius change rate
dVm = (V1 - V0) / dt
dRf = 1 / (Pi * V1 * R * R) * dVf - R / 3 / V1 * dVm

' Total number change rate
If (-dNc) > dNn Then
   dN = fcoa * dNc
Else
   dN = dNn
End If

R1 = R + dRf * dt
N = N + dN * dt
A1 = A + 4 * Pi * Db * dt
A2 = 1 / N

If A1 > A2 Then
   A = A2
Else
   A = A1
End If

Rc = (A / Pi) ^ 0.5
time = time + dt
If R1 > 0 Then
   R = R1
End If
V0 = V1
i = i + 1
BetaTheta = R / ((A2 / Pi) ^ 0.5)
ML = GRate * BRate * PRate / ((1 - BetaTheta * (1 + 2 * PreBetaFraction)) *
PRate * BRate + 2 * PreBetaFraction * BetaTheta * GRate * BRate + BetaTheta *
GRate * PRate) * 86400 * 0.5 * 2700


' Part VII - Final data output
If 25 < ML And SensitizedCheck = True Then
   SensitizedTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
```

```
    SensitizedCheck = False
  End If

  If ServiceML < ML And ServiceCheck1 = True Then
    ServiceTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)
    ServiceCheck1 = False
  End If

  If 40 < ML Then
    FailureCheck = True
    Exit Do
  End If

  If ML0 > ML - 0.0005 Then
    dt = dt * 2
  ElseIf ML0 < ML - 0.001 Then
    dt = Round(dt / 2, 0)
    If dt < 1 Then
      dt = 1
    End If
  End If

  ML0 = ML

  If time > 3.11 * 10 ^ 10 Then
    Exit Do
  End If

Loop

FailureTime = Math.Round(time / 3600 / 24 / 30 / 12, 2)

If ServiceCheck2 = True Then
  Cells(4, 11).Value = "Time Remaining to Threshold Sensitization, 25 mg/cm2 "
  Cells(5, 11).Value = "Time Remaining to High Sensitization, 40 mg/cm2 "
  If SensitizedTime - ServiceTime < 0 Then
    Cells(4, 13).Value = 0
  Else
    Cells(4, 13).Value = SensitizedTime - ServiceTime
  End If
  If FailureTime - ServiceTime < 0 Then
    Cells(5, 13).Value = 0
  Else
    Cells(5, 13).Value = FailureTime - ServiceTime
  End If
```

```
    Else
        Cells(4, 11).Value = "Time to Threshold Sensitization, 25 mg/cm2 "
        Cells(5, 11).Value = "Time to High Sensitization, 40 mg/cm2 "
            If SensitizedCheck = True Then
                Cells(4, 13).Value = ">1000"
                Cells(5, 13).Value = ">1000"
            ElseIf FailureCheck = False Then
                Cells(4, 13).Value = SensitizedTime
                Cells(5, 13).Value = ">1000"
            Else
                Cells(4, 13).Value = SensitizedTime
                Cells(5, 13).Value = FailureTime
            End If
    End If

End If
Sheets("Model").Protect Password:="ald1234"
Sheets("Data").Protect Password:="ald1234"

End Sub
```

REFERENCES

[1] R. Goswami and R. L. Holtz, Metall. Mater. Trans. A **44A**, 1279 (2013).

[2] R. Goswami, G. Spanos, P. S. Pao, and R. L. Holtz, Mater. Sci. and Eng. A **527**, 1089 (2010).

[3] R. B. Niederberger, J. L. Basil, and G. T. Bedford, Corros. **22**, 68 (1966).

[4] ASTM Standard G67, Standard test method for determining the susceptibility to intergranualar corrosion of 5XXX series aluminum alloys by mass loss after exposure to nitric acid (NAMLT test), (ASTM International, West Conshohocken, PA, 2013).

[5] J. G. Kaufman, *Introduction to Aluminum Alloys and Tempers* (ASM International, Materials Park, OH, 2000), pp. 11-21.

[6] M. Sharma and C. W. Ziemian, J. Mater. Eng. Perform. **17**, 870 (2008).

[7] R. H. Jones, J. S. Vetrano, and C. F. Windisch Jr., Corros. **60**, 1144 (2004).

[8] R. H. Jones, D. R. Baer, M. J. Danielson, and J. S. Vetrano, Metall. Mater. Trans. A **32A**, 1699 (2001).

[9] E. Romhanji and M. Popovic, Metalurgija J. Metall. **42**, 298 (2003).

[10] J. C. Chang and T. H. Chuang, Metall. Mater. Trans. A **30A**, 3191 (1999).

[11] C. F. Windisch *et al.*, presented at the 198th meeting of the Electrochemical Society (Phoenix, AZ, 2000).

[12] S. Nebti, D. Hamana, and G. Cizeron, Acta Metall. Mater. **43**, 3583 (1995).

[13] M. Kubota, Mater. Trans. **46**, 241 (2005).

[14] M. Kubota, Mater. Trans. **46**, 2437 (2005).

[15] M. J. Starink and A. M. Zahra, Acta Mater. **46**, 3381 (1998).

[16] R. Nozato and S. lshihara, Trans. Japan Inst. Met. **21**, 580 (1980).

[17] P. Villars, H. Okamoto, and K. Cenzual, *ASM Handbook* (ASM International, Materials Park, OH, 1992), pp. 3.

[18] P. M. Bernole, R. Graf, and P. Guyot, Philos. Mag. A **28**, 771 (1973).

[19] E. K. Boudilli, M. F. Denanot, and A. Dauger, Scripta Metall. **11**, 543 (1977).

[20] C. Gault, A. Dauger, and P. Boch, Acta Metall. **28**, 51 (1980).

[21] E. Kus, Z. Lee, S. Nutt, and F. Mansfeld, Corros. **62**, 152 (2006).

[22] M. M. Sharma and C. W. Ziemian, J. Mater. Eng. Perform. **17**, 870 (2008).

[23] J. L. Searles, P. I. Gouma, and R. G. Buchheit, Metall. Mater. Trans. A **32A**, 2859 (2013).

[24] G. Yi *et al*,. Miner. Met. & Mater. Soc., 2015.

[25] Y. Zhu *et al*., Metall. Mater. Trans. A **43A**, 4933 (2012).

[26] J. R. Pickens, J. R. Gordon, and J. A. S. Green, Metall. Trans. A **14A**, 925 (1983).

[27] N. Birbilis and R. G. Buchheit, J. Electrochem. Soc. **152**, B140 (2005).

[28] Z. Szklarska-Smialowska, Corros. Sci. **41**, 1743 (1999).

[29] S. J. McDanels, *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres*, Eight Volume (West Conshohocken, PA, 1997). Reprinted with permission.

[30] A. Barbucci, G. Bruzzone, M. Delucchi, M. Panizza, and G. Cerisola, Intermetallics **8**, 305 (2000).

[31] R. Holze, P. S. Pao, R. A. Bayles, T. M. Longazel, and R. Goswami, Metall. Mater. Trans. A **43A**, 2839 (2012).

[32] G. A. Gehring and M. H. Peterson, Corros.-Nace **37**, 233 (1981).

[33] T. H. Nguyen and R. T. Foley, J. Electrochem. Soc. **127**, 2563 (1980).

[34] Y. Yuan, Ph. D. thesis, University of Birmingham, 2005.

[35] L. I. Kaigorodova, Mater. Sci. Forum **294**, 477 (1999).

[36] P. N. T. Unwin and R. B. Nicholson, Acta Metall. **17**, 1379 (1969).

[37] N. Saito, M. Mabuchi, M. Nakanishi, and M. Nakamura, J. Mater. Sci. Lett. **18**, 41 (1999).

[38] L. Tan and T. R. Allen, Corros. Sci. **52**, 548 (2010).

[39] D. Mizuno and R. G. Kelly, Corros. Sci. **69**, 580 (2013).

[40] D. Mizuno and R. G. Kelly, Corros. Sci. **69**, 681 (2013).

[41] R. G. Kelly, J. R. Scully, and R. P. Gangloff, University of Virginia, 2007.

[42] M. L. C. Lim, J. R. Scully, and R. G. Kelly, Corros. **69**, 35 (2013).

[43] P. Schmutz and G. S. Frankel, J. Electrochem. Soc. **145**, 2285 (1998).

[44] P. Leblanc and G. S. Frankel, J. Electrochem. Soc. **149**, B239 (2002).

[45] T. S. Haung and G. S. Frankel, Corros. Sci. **49**, 858 (2007).

[46] K. A. Yasakau, M. L. Zheludkevich, S. V. Lamaka, and M. G. S. Ferreira, J. Phys. Chem. B **110**, 5515 (2006).

[47] E. V. Koroleva, G. E. Thompson, G. Hollrigl, and M. Bloeck, Corros. Sci. **41**, 1475 (1999).

[48] K. Mizuno, A. Nylund, and I. Olefjord, Corros. Sci. **43**, 381 (2001).

[49] W. Zhang and G. S. Frankel, Electrochim. Acta **48**, 1193 (2003).

[50] X. Liu, G. S. Frankel, B. Zoofan, and S. I. Rokhlin, J. Electrochem. Soc. **163**, B42 (2006).

[51] M. L. Zheludkevich, K. A. Yasakau, S. K. Poznyak, and M. G. S. Ferreira, Corros. Sci. **47**, 3368 (2005).

[52] G. Yi, M. Free, Y. Zhu, and A. Derrick, Metall. Mater. Trans. A **45A**, 4851 (2014).

[53] G. Yi, M. Free, Y. Zhu, and A. Derrick, manuscript (unpublished).

[54] H. O. K. Kirchner, Metall. Trans. **2**, 2861 (1971).

[55] I. M. Lifshitz and V. V. Slyozov, J. Phys. Chem. Solids **19**, 35 (1961).

[56] C. Wagner, Zeitschrift für Elektrochemie **65**, 581 (1961).

[57] S. Kar, Ph. D. thesis, University of Utah, 2012.

[58] M. Mortimer, Chemical Kinetics and Mechanism **1**, 86 (2002).

[59] G. Yi, collaboration, University of Utah, 2015

[60] Y. Zhu, Master thesis, University of Utah, 2012.